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Testing and Comparison of Several Mixed-Layer Models

Paul J. Martin
Ocean Sensing and Prediction Division
Ocean Science Directorate

Foreword

The upper ocean is an area of vital importance to naval operations. Changes in the density structure of this region due to atmospheric forcing can significantly affect the performance of both acoustic and nonacoustic sensors. Despite considerable observation and study, mixing processes in the upper ocean are still far from being fully understood. As a result, current models of these processes are fairly empirical and somewhat varied in their assumptions. The testing of mixed-layer models and the evaluation of their ability to reproduce the observed response of the upper ocean to atmospheric forcing is the most practical way to identify accurate and useful modeling parameterizations, and is an important step toward improving the Navy's upper-ocean prediction capability.

A. C. Esau, Captain, USN
Commanding Officer, NORDA

Executive summary

Several models of the upper mixed layer of the ocean (Mellor-Yamada Level 2 and 2½, Niiler, Garwood, Price, and Therry-Lacarrere) were compared using (a) idealized forcing that consisted of cases of wind deepening, heating, and cooling; (b) data from Ocean Stations November and Papa; (c) data taken during the Mixed-Layer Experiment (MILE); and (d) data taken from R/P FLIP in the spring of 1980 about 400 km off California. Comparisons with both idealized and observed forcing show the differences among the models to be significant. Differences are especially noticeable for the deepening of the mixed layer in the fall and winter due to wind mixing and convection, and for the shallowing of the mixed layer during light winds and strong heating. Although evaluation of the models is complicated by uncertainties (primarily with regard to advective effects and forcing), the results suggest certain deficiencies in some of the mixing parameterizations.

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Testing and comparison of several mixed-layer models

I. Introduction

Several mixed-layer (ML) models—the Mellor-Yamada Level 2 (MYL2) and Level 2½ (MYL2.5), Niiler, Garwood, Price, and Therry-Lacarrere (TL) models—were tested and compared for their suitability for use in operational ocean forecasting. These models are fairly representative of the current range of oceanic mixed-layer models, and are among the most commonly used. The models were evaluated primarily with respect to their accuracy in reproducing the observed response of the mixed layer. The computational requirements of the models on a VAX 11/785, the computer on which the simulations were performed, is also discussed.

The mixed-layer models described in the scientific literature vary considerably in terms of their formulation, complexity, and numerical efficiency (for a review see Garwood, 1979). One of the reasons for the wide variety of mixed-layer models in current use is that there is still a fair degree of uncertainty regarding the primary mechanisms responsible for turbulent mixing in the upper ocean. Mixing can be divided into two broad categories: forced convection, which is driven by the wind; and free convection, which is driven by vertical density instabilities. For forced convection, the possible mechanisms for mixing include surface and internal wave effects, shear instabilities, secondary circulations in the mixed layer (such as Langmuir cells), and interactions among these processes. For pure free convection, mixing is caused by buoyancy instabilities. However, there is little concurrence as to how much penetration (erosion of the stable region at the base of the mixed layer due to overshooting of the buoyant plumes) occurs in the ocean. In addition, since some wind is usually present, free convection in the ocean usually occurs in conjunction with some degree of forced convection.

Because of the degree of uncertainty regarding the validity of the parameterizations employed by mixed-layer models, probably the best way to evaluate them for use in a forecast model is to test them with as much data as possible. Most published mixed-layer studies involve the consideration of a single model, usually at a single location and often under a limited range of conditions. What we have attempted here is to intercompare a number of models with data from several locations that include a wide variety of conditions.

Data sets suitable for testing mixed-layer models are limited in number because they must include reliable meteorological observations for model forcing that resolve diurnal and synoptic variability, as well as adequate subsurface data for model initialization and verification. Additionally, it is best if advective effects, which are difficult to estimate, are minimal.

The mixed-layer models were tested using data from weathership stations November (N) and Papa (P), which are located in a relatively quiescent region of the eastern North Pacific; data taken during MILE (the Mixed-Layer Experiment), conducted near Papa in the fall of 1977; and data taken from the R/P FLIP about 400 km off California in the spring of 1980, which include high-resolution conductivity-temperature-depth (CTD) observations of the diurnal mixed-layer response. The different data sets have their particular advantages. The ocean station data allow testing on long time scales under a wide variety of seasonally varying conditions. The data from the mixed-layer experiments provide more accurate and extensive observations, but for a limited period of time.

In addition to testing with data, the models were compared for some simple, idealized forcing conditions that consisted of cases of wind-deepening, heating, and cooling. Such experiments are a means of isolating the models' performance in various mixing regimes. They provide an indication of how the models will respond to real forcing conditions and why the model predictions differ from each other and from the observed ocean response.

II. Description of mixed-layer models tested

Only a brief description of the models is provided here. For more detail the reader is referred to the papers cited. Table 1 provides a summary of the turbulence mechanisms employed by the models for mixing. Note that although two models may use the same mechanism, it may be implemented in different ways.

Table 1. Turbulence mechanisms used by the mixed-layer models. Note that the same mechanism may be implemented differently in different models.

model	type*	surface flux (u_*^3)	shear	convection	penetrative convection	depth-dependent dissipation
MYL2	diff	no	yes	yes	no	yes
MYL2.5	diff	not effective	yes	yes	very little	yes
Niiler	bulk	yes	only when deepening	yes	yes	not for u_*^3
Garwood	bulk	yes	not in version tested	yes	yes	yes
Price	bulk	no	yes	yes	no	yes
TL	diff	not effective	yes	yes	very little	yes

* diff = differential primitive equation mixed-layer model.
bulk = bulk or integrated mixed-layer model.

The models are of two basic types based on their method of formulation, differential and bulk. The MYL2, MYL2.5, and TL models are differential models in the sense that the equations for the conservation of momentum, heat, salt, and turbulent kinetic energy (TKE) are used in their primitive form and are not integrated over the mixed layer. The mixed layer for these models is defined by the region where the local TKE is large enough to provide a certain minimum level of vertical mixing. The Niiler, Garwood, and Price models are bulk (or integrated) models in which the mixed layer is assumed to be a well-defined layer that is uniform in temperature and salinity. The governing equations for the bulk models are obtained by integrating the primitive equations over the depth of the mixed layer.

The MYL2 model (Mellor and Yamada, 1974; Mellor and Durbin, 1975) is a differential model in which the rate of vertical mixing is described by eddy coefficients that depend on the local TKE. The TKE is calculated using a quasi-equilibrium form of the TKE equation in which shear production, buoyancy production, and dissipation are in local balance. For forced convection, the MYL2 model depends only on shear production (the instability of the Ekman current shear) to generate turbulence for mixing. The depth of mixing is determined by the depth where the shear instability is stabilized by the stratification, which is where where the Richardson number (the ratio of buoyancy production to shear production) exceeds a critical value (about 0.23 for the MYL2 model). Since shear production is the only source of TKE where the density gradient is locally stable, the MYL2 model predicts no convective penetration, only a convective adjustment where the mixing is just sufficient to relieve the density instability.

The MYL2.5 model (Mellor and Yamada, 1977 and 1982) is similar to the MYL2 model, except that the TKE equation includes storage and diffusion of TKE. The diffusion term should (ideally) provide a means for supplying TKE to the base of the mixed layer for penetrative convection. However, the gradient approximation that is used in the MYL2.5 model for this term has been generally criticized as being inadequate for describing this process (Zeman and Lumley, 1976). The MYL2.5 model also employs slightly different turbulence constants that result in a smaller critical Richardson number (about 0.20).

The Niiler model (Niiler, 1975; Davis et al., 1981b) is a bulk mixed-layer model. The depth of mixing is governed by an integrated form of the TKE equation, which includes a surface flux of TKE from wave effects (often called the u_*^3 term), shear production, and a fixed amount of penetrative convection. When the mixed layer is deepening, all the terms in the TKE equation are accounted for. However, when shallowing, the shear term is not included and the mixed-layer depth (MLD) is determined by a balance between the surface flux of TKE and buoyancy production.

The Garwood model (Garwood, 1977) is also a bulk mixed-layer model. This model includes separate budgets for the horizontal and vertical components of TKE. The TKE equations account for a surface flux of TKE from waves and for penetrative convection. The model includes a dissipation term that is proportional to the Coriolis parameter to account for the effects of the earth's rotation on TKE dissipation. The version of the model used here does not include shear production of TKE since Garwood (1977) found that this term did not significantly affect the depth of mixing predicted by the model. Therefore,

the model does not require the calculation of the momentum budget, which reduces the amount of calculation required for a one-dimensional simulation.

The Price model (Price et al., 1986) depends only on shear and density instability for mixing, and in this sense it is similar to the MYL2 model although it has a bulk formulation. For forced convection, the depth of mixing is governed by a bulk critical Richardson number (0.65), and for free convection it (like the MYL2 model) provides for a convective adjustment but no convective penetration. The formulation of the Price model differs from that of the other bulk models in that the temperature, salinity, and momentum profiles at the base of the mixed layer are smoothed every time step using a local Richardson number criteria. This has the effect of creating a smooth transition region at the base of the mixed layer rather than the sharp jump or discontinuity common to most other bulk models.

The TL model (Therry and Lacarrere, 1983) is a differential model. It is similar to the MYL2.5 model, but includes a parameterization of counter-gradient buoyancy fluxes and a more elaborate formulation of the diffusion of TKE to improve the description of free convection. The critical Richardson number of the TL model is about 0.47.

A brief word is in order about the tuning or adjustment of the model constants for the models tested here. Since optimum values for many of the constants that scale the processes parameterized by the models have not been firmly established, there is some leeway in setting the values for these constants. A practical goal is to find the values for the model constants that give consistently good predictions in different regions over the entire range of expected conditions. If a model consistently under- or overpredicts the mixed-layer depth by a similar amount, the model constants can generally be adjusted to correct the problem. However, having to use different model constants to get good results in different regions or situations suggests that the model parameterizations themselves are lacking.

The constants for the models tested here were defined as reported in the references cited with the following exceptions. The scaling factor for the turbulent length scale for the MYL2 and MYL2.5 models was increased from 0.1 to 0.2 to increase the rate of mixing in the mixed layer. The values for the Niiler model constants were as recommended by Davis et al. (1981b) from simulations with the MILE data. The constants scaling the entrainment flux at the base of the mixed layer and the "rotational" dissipation term for the Garwood model were set to 4.5 and 4.6, respectively, based on the results of simulations at Stations November and Papa.

III. Comparison of mixed-layer models for some simple forcing cases

The mixed-layer models were tested for three types of idealized forcing to compare their response to simple forcing conditions. The forcing was chosen to represent three basic regimes: wind-deepening, heating, and cooling.

Wind-deepening is defined to occur when the mixed layer deepens due to the erosion of the stably stratified region at its base by wind-generated turbulence. The depth of mixing is governed by the strength of the density stratification and the magnitude of the wind.

In the heating regime the mixed-layer depth is governed by a balance between the stabilizing effect of surface heating (or a positive surface buoyancy flux) and the effect of mixing due to wind-generated turbulence. This balance governs the mixed-layer depth during periods when the mixed layer is shallowing.

In the cooling regime, a net surface heat loss (or a negative surface buoyancy flux) causes the mixed layer to deepen due to convection. Convection usually occurs in the mixed layer at night after sunset, and is the dominant mechanism for the deepening of the mixed layer in the fall and winter when solar heating is weak and there is increased evaporative cooling from the wind.

The density stratification and forcing for these tests were chosen to be representative of conditions in midlatitudes.

A. Wind-deepening

For the wind-deepening experiments the initial conditions were taken to be sea-surface temperature (SST) equal to 24°C, thermal stratification a uniform 0.05°C/m, salinity a constant 35 ppt, and Ekman velocity zero. The latitude was taken to be 29.91°N where the inertial period is 24 hours. For each of the models, three different cases of wind-deepening were run with wind stress values of 1, 4, and 16 dynes/cm^2. The surface heat and salinity fluxes were zero.

The mixed-layer depth for each of the models after 5 days is listed in Table 2. Figure 1a shows mixed-layer depth versus time for the 4 dynes/cm^2 wind-stress case. From Table 2 it can be determined that the predicted mixed-layer depth is approximately proportional to the square root of the wind stress for all the models.

Table 2. Comparison of response of mixed-layer models to simple forcing.

A. Wind-deepening: Linear initial stratification (0.05°C/m), constant wind stress, no surface heat flux. Table values are mixed-layer depth in meters after 5 days.			
Wind stress (dynes/cm^2) =	1	4	16
Mellor-Yamada Level 2	19	41	76
Mellor-Yamada Level 2½	18	39	76
Niiler	27	54	108
Garwood	26	51	104
Price	20	44	88
Therry-Lacarrere	22	46	87
B. Heating: Small initial stratification, constant wind stress (1 dyne/cm^2), constant heat flux. Table values are mixed-layer depth in meters after 2 days.			
Surface heat flux (ly/day) =	150	600	2400
Mellor-Yamada Level 2	28	16	8
Mellor-Yamada Level 2½	28	16	8
Niiler	17	4	1
Garwood	33	14	4
Price	36	18	10
Therry-Lacarrere	38	20	10
C. Cooling: Linear initial stratification (0.05°C/m), constant wind stress (1 dyne/cm^2), constant heat flux. Table values are mixed-layer depth in meters after 120 days.			
Surface heat flux (ly/day) =	−100	−200	−300
Mellor-Yamada Level 2	72	105	122
Mellor-Yamada Level 2½	72	104	122
Niiler	101	127	150
Garwood	90	117	140
Price	71	102	126
Therry-Lacarrere	76	104	126

The MYL2, MYL2.5, Price, and TL models show a similar response to the wind-forced deepening of the mixed layer. There is a rapid deepening during the first day, and a very gradual deepening thereafter. This behavior is characteristic of the shear instability mechanism that these models employ. The small, inertial period oscillation of the mixed-layer depth for these models is caused by residual stratification within the mixed layer and the fluctuating shear at the base of the mixed layer due to inertial motions. The primary reason for the difference in mixed-layer depth between the MYL2, MYL2.5, and TL models is due to the difference in critical Richardson number—a higher value of the critical Richardson number tends to generate a deeper mixed layer. The diffusion of TKE in the MYL2.5 model appears to have little effect on the mixed-layer depth for these cases of forced convection.

The Niiler model responds on two distinct timescales. The rapid deepening of this model during the first 12 hours is due mainly to the shear production term in the TKE equation, and the more gradual deepening that follows is due to the surface TKE-flux term (Niiler, 1975). It is notable that the Niiler model responds much more quickly than the MYL2, MYL2.5, TL, and Price models in spite of the fact that the same mechanism, shear production, is primarily responsible for the deepening. The difference in response time seems to be due to the instantaneous mixing of heat and momentum within the mixed layer that is inherent in the bulk formulation of the Niiler model. The Garwood model, which does not include shear production, responds a little less quickly than the Niiler model during the first 12 hours, but then begins to catch up and is almost as deep after a few days. The persistent deepening of the Niiler and Garwood models, relative to the others, that occurs after the first day is due to the surface TKE flux term.

B. Heating

For the heating experiments, the initial conditions and model parameters were as for the wind-deepening experiments except that the initial temperature from the surface to 100 m was a uniform 19°C. The models were forced with a constant wind stress of 1 dyne/cm^2 and heat fluxes of 150, 600, and 2400 ly/day (1 ly = 1 cal/cm^2). (For reference, the mean rate of heating through the spring and summer in midlatitudes is about 150 ly/day, although daily peaks can be as high as 100 ly/hour.)

The mixed-layer depths predicted for the heating experiments are listed in Table 2. The Niiler and Garwood bulk models respond instantly to a change in the surface forcing when shallowing because the time derivative terms in the entrainment equation are dropped when shallowing and the new mixed-layer depth is solved for algebraically. The response of the other models to surface heating depends on the strength of the forcing, but is on the order of a few hours as increasing stratification suppresses turbulent mixing below a certain depth. On diurnal and longer timescales this difference in response is not very noticeable in the model results.

The MYL2, MYL2.5, Price, and TL models predict similar mixed-layer depths. As in the wind-deepening case, the differences in mixed-layer depth are primarily governed by the differences in critical Richardson number, which determines the balance between the buoyancy and shear production terms in the TKE equation. It should be pointed

out that the mixed layer for the differential models (MYL2, MYL2.5, and TL) shows a significant amount of stratification when surface heating is present. The eddy coefficients do not mix the mixed layer rapidly enough to keep the temperature in the mixed layer uniform.

For these heating experiments where the source of heat is at the surface (i.e., there is no penetration of solar radiation), the mixed-layer depth for the Niiler model is proportional to the Obukov length (the ratio of the surface flux of TKE to buoyancy production). The Niiler model shows a stronger dependence on the surface buoyancy flux than the other models where the mixed-layer depth for the shallowing case depends on the Ekman length scale, as well as the Obukov length.

The Garwood model shows a stronger response to surface heating than the MYL2, MYL2.5, Price, and TL models when the surface heat flux is high, but does not get as shallow as the Niiler model.

An idiosyncrasy of the Price model is that the mixed-layer depth undergoes an oscillation when the mixed layer is shallowing under the influence of a constant surface heat flux and wind stress. The effective mixed-layer depth is determined by the bottom of the envelope of these oscillations, since this is the region that is kept mixed. The oscillation is inherent in the algorithm used by the model. Although a bit disturbing, this behavior does not have an evident effect on the predicted density and momentum profiles.

C. Cooling

For the cooling experiments the initial conditions and model parameters were the same as for the wind-deepening experiments. The models were forced with a constant wind stress of 1 dyne/cm^2 and surface heat fluxes of -100, -200, and -300 ly/day. (The mean surface heat flux in midlatitudes from October through January is on the order of -150 ly/day.) Table 2 lists the mixed-layer depths predicted by the models after a period of 120 days, and Figure 1b shows mixed-layer depth versus time for the -200 ly/day case.

Observations of convective boundary layers in the atmosphere and in the laboratory indicate that convective penetration is usually sufficient to generate an entrainment buoyancy flux at the base of the mixed layer that is 10–30% of (but opposite in sign to) the surface-driving buoyancy flux (Stull, 1976). For the cooling experiment of Figure 1b this would result in a final mixed-layer depth of 108–125 m, whereas simple convective adjustment would produce a final mixed-layer depth of 99 m.

The shallowest mixed-layer depths are for the MYL2, MYL2.5, Price, and TL models, which give similar results. For pure convection (no wind stress) the MYL2 and Price models can provide no more than a convective adjustment of the density profile. Local shear production provides the only source of TKE for mixing for these models when the local density gradient is stable. However, for a mixed layer deeper than 70 or 80 m the shear of the wind-driven current is too weak at the base of the mixed layer to provide much entrainment mixing during typical wind conditions.

For the MYL2.5 and TL models, the diffusion term in the TKE equation can supply TKE for convective penetration. However, the fact that the mixed-layer depths predicted by these models are similar to those predicted by the MYL2 and Price models indicates that the parameterization used for this term is not very effective in generating convective penetration. This was noted by Mellor and Yamada (1977) for the MYL2.5 model in simulating the laboratory convection experiments of Willis and Deardorff (1974). Therry and Lacarrere (1983), on the other hand, obtained a negative heat flux overshoot of about 15% with their model in simulations of the Wangara atmospheric boundary layer experiment. The reason for this discrepancy with the results here is not known.

The Niiler model is adjusted to dissipate 83% of the TKE generated by the buoyancy term during free convection. Hence, the TKE used for entrainment mixing is 17% of that generated by the buoyancy term plus the surface flux of TKE whose relative importance decreases with increasing mixed-layer depth. In a test made without the surface TKE flux term with a surface heat flux of -200 ly/day, the final mixed-layer depth was reduced from the 127 m of Figure 1b to 118 m.

For free convection the Garwood model dissipates 73% of the TKE generated by the buoyancy term when the mixed layer is very shallow, which is less than the Niiler model. However, this percentage increases as the mixed layer deepens (as long as the Coriolis parameter is not zero), and in Figure 1b the Garwood model deepens less rapidly than the Niiler model below 50 m.

IV. Mixed-layer model testing at Ocean Stations November and Papa

Three-hourly surface meteorological and subsurface bathythermograph (BT) observations have been collected at the ocean weathership stations in the North Atlantic

and North Pacific since the 1940s. This is probably the best available data for testing mixed-layer models on synoptic to interannual time scales. Although we are interested here in evaluating mixed-layer models for short time-scale predictions, there are a number of advantages in testing the models on longer time scales. The models are forced by a wide range of seasonally varying conditions, and biases in the model results can be easier to discern when the simulations are carried over a long period of time.

Stations November and Papa are located in the eastern North Pacific at 140°W, 30°N and 145°W, 50°N, respectively. Data for the years 1960–1970 were investigated for both stations. Because of large gaps in the BT data at Station November for most of the other years, 1961 was chosen for testing the mixed-layer models.

A. Initialization and forcing from ocean station data

The BT observations were used to initialize the temperature profiles and verify the model-predicted SST and mixed-layer depth. The inclusion of salinity in the simulations was hindered by a lack of salinity and precipitation data. At Station November salinity was taken to be constant, since the effect of salinity on the density stratification of the upper ocean in this region is generally small. At Station Papa the depth of mixing in winter is limited by the strong halocline which exists below 100 m where the thermal stratification becomes relatively weak. Therefore, to prevent an unrealistically deep winter mixed layer, the salinity profile at Papa was initialized from climatology (Beatty, 1977). Model experiments at Station Papa in which precipitation was estimated showed that surface salinity fluxes generally have only a small effect on vertical mixing, and these fluxes were set to zero for the results shown here.

The meteorological data taken at Stations November and Papa include SST, air and wet bulb temperature, wind speed and direction, and cloud cover. From these observations, standard formulas were used to calculate surface fluxes of momentum and heat (see Martin, 1985). Solar radiation was calculated using the Fritz formula for clear-sky insolation (List, 1958), which provides a proper diurnal variation. The Reed (1977) cloud cover correction was used for Station November and the Tabata (1964) correction for Papa. The albedo was taken to be 6%. Seawater turbidity, which has a significant effect on the depth of penetration of solar radiation and, as a result, the development of the upper ocean thermal structure in spring and summer (Martin, 1985), was taken to be Type I at November and Type II at Papa (Jerlov, 1976).

B. Results of mixed-layer simulations at Ocean Stations November and Papa

The observed and model-predicted three-hourly SST and mixed-layer depth at Stations November and Papa are shown in Figures 2 and 5, and Figures 3 and 6 show predicted minus observed SST for the two stations. The mixed-layer depth for both the observations and the simulations is defined as the depth at which the temperature becomes 0.1°C less than the SST. A different criterion for defining mixed-layer depth, such as a temperature difference of 0.2°C, misses a few of the shallow, short-term mixed layers, but gives a similar envelope on the synoptic time scale for both the observations and the model results.

The SST determined from the BT data at November has a few seemingly spurious features that should be kept in mind when comparing the model results with the observations. The more notable of these are a drop of about a degree during the middle of January, a sudden increase of about a degree during the beginning of September that lasted about a week (this feature is corrected for in Figs. 2 and 3), and three abrupt changes near the beginning and end of October. These SST features are not reflected in the mixed-layer depth or surface meteorological observations, hence they are not caused by surface forcing and are not reproduced by the models. They do not seem to be associated with a change of the reported location of the observations, but they do frequently coincide with a change of the ship on station.

Generally, fluctuations in the observed SST and mixed-layer depth on the synoptic time scale tend to be well correlated with the surface forcing and, as a result, can be seen in the model simulations. In fall and winter the variability predicted by the models is less than observed. Especially noticeable are the shallow mixed layers that occur at Station November during the winter months. These are stabilized by temperature jumps of up to 0.8°C and appear to be due to advection.

All the models predicted a premature, overly abrupt spring shallowing of the mixed layer at Station November. This could be due to advection or to an overestimate of the surface heat flux during this period. The time of the spring shallowing at Papa, however, is predicted on schedule. All the models predicted a colder SST at Papa than observed in the fall, even those that underpredicted the mixed-layer depth. The heat content of the mixed layer at Papa at this time cannot be accounted for by the surface heat flux, and must have been due to a net advection of heat into this region.

The MYL2 and MYL2.5 models underpredict the mixed-layer depth at both November and Papa. As a result the predicted SST is about 1.5°C too high in the summer. Advective effects or insufficient mixing are the most likely causes of the underpredicted mixed-layer depth. It is difficult to determine if advection is the source of the discrepancy. However, evidence that the MYL2 and MYL2.5 models do not provide enough entrainment mixing is that the temperature gradient at the base of the mixed layer is often significantly less than observed, especially in late summer and fall at Station November (Fig. 4). It may be that the shear production parameterized by these models is insufficient to describe forced convection in the ocean or that the models predict too little penetrative convection.

The TL model gives fairly good results at Papa, and better results at November than the MYL2 and MYL2.5 models, although the mixed-layer depth at November is still shallower than observed. The improvement over the MYL2 and MYL2.5 models is primarily due to the larger critical Richardson number that the TL model employs.

The Niiler model does fairly well in simulating the seasonal evolution of SST and mixed-layer depth at Station November. However, the predicted mixed-layer depth at Papa is too deep and the summer SST is underpredicted by about 3°C. Station Papa has stronger winds than November and a much weaker main thermocline, which provides less resistence to erosion in winter. When deepening, the Niiler model takes into account TKE generated by mean shear, the surface flux from waves, and convection. However, when shallowing, only the surface flux of TKE from waves balances buoyancy production. Hence, the scaling of the surface flux must be sufficiently large to produce realistic mixed-layer depths when shallowing, and this term may be too large when the mixed layer is deepening.

The mixed-layer depth predicted by the Garwood model at November agrees well with the observations through much of the year, but is a little shallower than observed in the summer, particularly during periods of light winds. At Papa the agreement between the Garwood model and the observations is very good through midsummer, although the predicted mixed-layer depth is slightly deeper than observed in the fall. The agreement was not improved by additional model tuning; e.g., decreasing the surface flux of TKE or increasing the dissipation tends to make the mixed layer too shallow in summer. However, some of the discrepancy may be due to the net advection of heat that appears to have occurred at Papa in the fall.

The Price model gives results similar to the TL model, a fairly good prediction of mixed-layer depth at Papa, but too shallow at November. In fact, this problem was found with all the mixing parameterizations that were tried which depend on shear-generated turbulence as the primary mixing mechanism for forced convection. It may be that shear is insufficient as a mixing mechanism for forced convection, or that some other error, such as neglect of advective effects at November, is causing the discrepancy.

V. Mixed-layer model testing with data from MILE

MILE was conducted near ocean station Papa (50°N, 145°W) in the eastern North Pacific in August and September 1977. This experiment was specifically conducted to investigate the upper mixed layer and to provide data against which models could be tested. Davis et al. (1981a,b) analysed some of the data from MILE and used the Niiler model to simulate the response of the mixed layer during the experiment to local atmospheric forcing. They noted that advective contributions to the upper ocean heat budget during MILE were generally small, but not negligible, and parameterized the effects of advection in their model simulations. The model testing with the MILE data reported here is based on their work. However, no attempt was made to parameterize advective effects. The local heat budget in the model simulations is due only to the surface heat flux.

A. Model initialization and forcing with the MILE data

At MILE mooring 1, temperature data were taken at fixed depths from 5 to 175 m at intervals of 112.5 sec from August 19 to September 7. This data was used to initialize and validate the models.

Meteorological observations were taken from the Canadian weathership *Quadra* at 3-hour intervals. Standard formulas were used to calculate the surface wind stress, net longwave radiation, and latent and sensible heat exchange from the wind speed and direction, air temperature and humidity, and cloud cover. Solar radiation was measured directly aboard the *Quadra* at hourly intervals.

B. Results of mixed-layer simulations with the MILE data

A comparison of model-predicted and observed 5-m temperature and mixed-layer depth for simulations with

the MILE data for all the models is shown in Figure 8. The temperature at 5-m depth was used for comparison because there are no reliable measurements of the actual SST during MILE. The mixed-layer depth is again defined as the depth at which the temperature is 0.1°C less than the surface temperature.

The observed 5-m temperature during MILE shows the steady warming of the ocean that was still occurring late in the summer. The steady warming was modulated by a diurnal fluctuation of 0.2–0.3°C caused by daytime solar heating and nighttime cooling. A cooling event occurred on August 22 and 23 caused by an increase in the winds, and a smaller cooling event occurred at the end of August.

The models generally predict the trend and the diurnal fluctuation of the 5-m temperature fairly well. None of the models predicted as much cooling as occurred on August 22 and 23, even those that predicted the observed amount of mixed-layer deepening, which indicates that some of the cooling at that time was due to advection.

The 5-m temperature and mixed-layer depth predicted by the MYL2 model agree fairly well with the observations. The major discrepancy is that the model underestimates the amount of cooling that occurred on August 22 and 23. Part of the discrepancy is due to an underestimate of the mixed-layer deepening, and part to advection not accounted for in the model simulations. As a result of underpredicting the cooling on August 22 and 23, the 5-m temperature predicted by the MYL2 model remains biased by about 0.4°C for the rest of the experiment. For a simulation initialized on August 25, after the cooling event, the MYL2 model tracks the observed 5-m temperature very well (Fig. 9). The MYL2.5 model, as at Stations November and Papa, gives results similar to the MYL2 model, but with a slightly shallower and, as a result, warmer mixed layer.

The Niiler model gives a good prediction of mixed-layer depth during the cooling event of August 22 and 23, but afterward generally overpredicts the mixed-layer depth and the mixed layer warms less quickly than observed. The Garwood, Price, and TL models give similar results, which lie between those of the models discussed previously, and show fairly good overall agreement with the observed 5-m temperature and mixed-layer depth.

VI. Mixed-layer model testing with data from R/P FLIP

A useful data set for mixed-layer model testing was obtained from R/P FLIP in April and May 1980 about 400 km west of San Diego, California, at about 30°N. The frequent CTD observations that were taken provide a detailed look at the response of the mixed layer to diurnal solar forcing under a variety of wind conditions. Price et al. (1986) reported on the observations and on simulations of the mixed-layer response using the Price mixed-layer model. The mixed-layer simulations performed for model testing here were based on their study.

A. Model initialization and forcing with FLIP data

Temperatures taken by a profiling CTD every 120 sec with a vertical resolution of 1 m were used to initialize and validate the models. The uppermost temperature measured was at a depth of 2 m.

Surface wind stress, net longwave radiation, and latent and sensible heat exchange were calculated from half-hourly meteorological observations using standard formulas. Solar radiation was measured directly with an Eppley pyranometer.

There were significant advective effects during most of the experiment. However, for a 4-day period between May 7 and 11 (Julian day 128–132), advective effects were minimal (Price et al., 1986), and this period was used for model testing.

B. Results of mixed-layer simulations with FLIP data

Figure 10 shows hourly observed and model-predicted temperature profiles for May 9 and 10. During the preceding two days the winds were moderate (8–12 m/sec) and the mixed layer stayed fairly well mixed down to about 40 m near the top of the seasonal thermocline. During the two days shown the winds were light (3–7 m/sec) and a shallow mixed layer formed in response to diurnal solar heating.

Notable features in the observed profiles are that (1) there is almost always a fairly well-mixed surface layer, i.e., the temperature in the surface layer is quite uniform; and (2) there is a fairly smooth transition region at the base of the mixed layer. The uniformity of the mixed layer may be due to the Langmuir-type circulations observed (Weller et al., 1985), since such overturning circulations can mix very rapidly. The transition region at the base of the well-mixed layer appears to be a region where the mixing rates are considerably reduced, but are still significant.

The MYL2 and MYL2.5 models again show similar results. Consistent with the findings at Stations November

and Papa, the mixed layer is not quite as deep as observed. Also apparent here, when compared to the highly resolved CTD profiles, is that there is often more stratification in the mixed layer than observed, which suggests that the rate of mixing in the mixed layer predicted by these models is too slow. This occurs both during the day when there is heating, and at night when there is cooling and convection. These turbulent diffusion models were developed to describe turbulent boundary layers over rigid surfaces, and do not account for circulations that might have the same scale as the boundary layer and cause more rapid mixing over the mixed layer than smaller scale turbulent eddies. The diffusion models do, however, provide the kind of smooth transition region at the base of the mixed layer seen in the FLIP CTD observations.

The Niiler model predicts a shallower mixed layer than observed when there is strong heating and light winds. From the idealized forcing experiments we know that this model responds much more strongly than the others to a high surface heat flux. The FLIP data suggest that this response is too strong. The Garwood model responds less strongly than the Niiler model to these conditions, but still more strongly than observed. Also, the bulk parameterization used in the Niiler and Garwood models gives a sharper gradient at the base of the mixed layer than observed in the FLIP CTD profiles.

The Price model gives a good simulation of the FLIP data. The SST and mixed-layer depth agree fairly well with the observations, and the bulk Richardson number deepening criteria, combined with a local Richardson number criteria for smoothing the profile at the base of the mixed layer, generates a realistic-looking (compared to the FLIP CTD observations) temperature profile.

The mixed layer predicted by the TL model is slightly deeper than predicted with the MYL2 and MYL2.5 models, which seems to give better agreement with the observations. But, as with the other differential models, the mixed layer is not as well mixed as observed.

VII. Computational requirements for the mixed-layer models

For a mixed-layer model applied at a single location for a forecast of short duration, the computer time and storage requirements of the models considered here are relatively small. However, if a mixed-layer model is run for a long period of time or is applied at a large number of points, the time and/or storage requirements can become significant.

Table 3 lists the central processor (cp) time required for a 1-day forecast at a single location with the various models. The timings were done on a VAX 11/785, a scalar (nonvectorizing) computer with a calculation speed of about 300,000 operations per second. The performance of the differential models (MYL2, MYL2.5, TL) relative to the bulk models would be considerably better on a vectorizing computer because of the high degree of vectorizability of the differential models.

Table 3. Central processor (cp) time used by mixed-layer models for 1-day simulation on VAX 11/785 computer.

model	timestep	cp time
Mellor-Yamada Level 2	10 min	3.0 sec
Mellor-Yamada Level 2½	10 min	7.0 sec
Niiler	1 hr	0.4 sec
Garwood	1 hr	0.1 sec
Price	1 hr	1.0 sec
Therry-Lacarrere	10 min	5.0 sec

The cp times in Table 3 must be qualified by the following comments. First, the numerical algorithms used were not necessarily developed for maximum efficiency. The differential models (MYL2, MYL2.5, and TL) and the Niiler bulk model were programmed inhouse at NORDA for research purposes with the emphasis on ease of use and modification, rather than on maximum speed. The algorithms for the Garwood and Price bulk models were obtained from their authors. The differential models have the potential to be speeded up by a factor of 2 or 3 by using more efficient algorithms. The Niiler and Price bulk models have some potential for being speeded up as well. The Garwood model, however, appears to be fairly efficient in its present form.

Second, the computer time required for a model simulation depends on grid resolution, timestep, number of grid points and, to some degree, the particular circumstances of the simulation. The times listed in Table 3 are based on an average of the times required for the simulations reported here with the November, Papa, MILE, and FLIP data, and thus represent a wide range of conditions. The times are also based on the use of a stretched grid of 45 points from the surface to 300-m depth with a resolution of 2 m at the surface. Such a grid has adequate resolution and depth for most applications. The model timestep used in determining the model cp times was 10 min for the differential models and 1 hr for the bulk models. The timestep for the bulk models is limited by the need to

resolve the variability in the surface forcing and to resolve the bulk or integrated response of the mixed layer to that forcing. The timestep for the differential models, on the other hand, is further limited by the need to provide an accurate treatment of the vertical diffusion terms. Although the diffusion terms are treated implicitly, instabilities can develop if the timestep is too much larger than the diffusive timescale based on the grid spacing (the diffusive timescale equals the square of the grid spacing divided by the eddy diffusion coefficient).

The cp times listed in Table 3 range from 7 to 0.1 sec per model day, with the MYL2.5 model being the slowest and the Garwood model the fastest. The differential models generally require more computation than the bulk models because of the need to use a smaller timestep. The differences in speed among the differential models is due to the increased computation required in the eddy coefficient algorithms for the TL and MYL2.5 models where the mean TKE equation must be solved. Of the bulk models, the Price model is somewhat slow because of the time consumed by the relaxation scheme used to adjust the transition region at the base of the mixed layer. The speed of the Garwood model is due to its simplicity (the momentum budget is not required) and the use of efficient algorithms to calculate changes in mixed-layer depth.

The computational disadvantage of differential models with respect to bulk models (due to the smaller timestep required) is somewhat offset on large "vectorizing" computers because of the high degree of vectorizability of the differential models; i.e., the same computations are performed at each grid point each time step. The algorithms for bulk models tend to be difficult to vectorize, since different sequences of calculations are performed at different points.

For applications requiring more (or less) resolution, changing the grid resolution affects the time requirements of the models differently. For the bulk models, increasing the grid resolution results in a somewhat less than proportional increase in the cp time required; e.g., doubling the grid resolution and the number of grid points may increase the cp time from 10 to 100% depending on the amount of grid-dependent calculation involved. For the differential models, a doubling of the grid resolution generally requires a four-fold decrease in the time step to maintain the accuracy of the vertical diffusion terms. Since decreasing the timestep increases the cp time proportionally (true for all the models tested here), doubling the grid resolution for the differential models results in about a 6- to 8-fold increase in the cp time required.

VIII. Summary

Table 4 summarizes the results from the mixed-layer model testing with the November, Papa, MILE, and FLIP data, and Table 5 summarizes the general pros and cons of the mixed-layer models.

Table 4. Specific model results from mixed-layer model testing.

model	results
MYL2	Underpredicts MLD at both N and P. ML not as well-mixed or as deep as observed with FLIP data.
MYL2.5	Gives results similar to MYL2. Gradient diffusion of TKE provides little modification of predicted MLD, even for the convective case.
Niiler	Good prediction of MLD at N. Overpredicts MLD at P where main thermocline is weak, due to insufficient dissipation when ML is deep. Overly strong response to high heat flux/light winds with FLIP data. Gradient at the base of the ML generally sharper than observed.
Garwood	Fairly good predictions at N and P, although model tends to shallow too much in midsummer, especially when winds are light. Response to light winds/high heat flux with FLIP data may be too strong. Gradient at base of mixed layer generally sharper than observed.
Price	MLD not as deep as observed at N. Good prediction at P. Good simulation of FLIP data.
TL	MLD too shallow at N, fairly good at P. ML not as well-mixed as observed with FLIP data.

The MYL2 and MYL2.5 models tend to underpredict the mixed-layer depth. The TL model, which has a larger critical Richardson number, predicts a slightly deeper mixed layer that generally agrees better with the observations (although the mixed-layer depth is still underpredicted at November). With a change in turbulence constants to increase the critical Richardson number, the MYL2 and MYL2.5 models would also give better agreement with the observed mixed-layer depth.

The mixed layer predicted with all the differential models (MYL2, MYL2.5, and TL) was not as well mixed (uniform) as shown by the high-resolution CTD profiles taken from FLIP. This evidence suggests that the eddy coefficients predicted for the mixed layer by these models are not giving as rapid mixing as actually occurs. This deficiency could be partially alleviated by increasing the turbulent mixing scale in these models (the resulting increase of the eddy coefficients would require a decrease in the timestep to

Table 5. Pros and cons of mixed-layer models.

model	pro	con
MYL2	Smooth transition at ML base. Potential to predict current shears. Very vectorizable.	ML too shallow. ML not sufficiently well-mixed. Not very fast.
MYL2.5	Same as MYL2. TKE diffusion helps stabilize numerics.	Same as MYL2. Slowest of models tested.
Niiler	Large number of TKE generation mechanisms provides flexibility.	Insufficient dissipation for deep ML. Shear not accounted for when shallowing. ML too shallow with high heating/light winds. Discontinuity at ML base.
Garwood	Fast. No momentum budget needed.	Shear mixing not explicitly accounted for. ML may be too shallow with high heating/light winds. Discontinuity at ML base.
Price	Simple. Smooth transition at ML base.	Constant positive heat flux causes oscillation of MLD. Somewhat slow for bulk ML model. May not mix deep enough in some situations.
TL	Same as MYL2.5	ML not sufficiently well-mixed. May not mix deep enough in some situations.

maintain the accuracy of the diffusion terms). The differential models do predict one of the significant features of the FLIP temperature profiles—a smooth transition (gradient) at the base of the mixed layer.

The Niiler bulk model gives a good simulation of SST and mixed-layer depth at November, but predicts too deep a mixed layer at Papa and with the MILE data. The FLIP data, in turn, suggest that this model predicts too shallow a mixed layer when the winds are light and the heating is strong. These problems can be traced to several shortcomings. There is not enough dissipation of the surface flux of TKE when the mixed layer is deep; and the production of TKE from shear instability, which is taken into account when the mixed layer is deepening, is not accounted for when the mixed layer is shallowing. The FLIP observations also indicate that the gradient predicted by the Niiler model at the base of the mixed layer is overly sharp, a characteristic of most bulk mixed-layer models.

The Garwood bulk model gave the best overall agreement for the annual simulations at both November and Papa. The model did benefit from being tuned somewhat to these two data sets, although some improvement could probably be achieved with additional experimentation. At November, the model was a little too shallow in the summer, and at Papa the model tended to be too shallow in the summer or too deep in the fall depending on model tuning. The FLIP data indicate that the model may shallow too much when strong heating and light winds occur, though not as severely as the Niiler model. As with the Niiler bulk model, the Garwood model predicts a sharper gradient at the base of the mixed layer than is observed.

The Price model does not predict as deep a mixed layer as observed at November, but gives fairly good predictions with the other data sets. It gives the best simulation of the CTD observations of the diurnal mixed-layer cycle taken from FLIP, where the combination of using a bulk Richardson number to deepen the mixed layer combined with a gradient Richardson number to diffuse the interface generates temperature profiles that have much of the character of those observed. The relaxation scheme used for diffusing the interface, however, results in the Price model being relatively slow for a bulk model. When forced with a steady, positive surface heat flux and wind stress the Price model's mixed-layer depth undergoes an oscillation that is inherent in the algorithm used. However, the oscillation does not appear to significantly affect the predicted profiles.

The running times per model day for the models (central processor time on a VAX 11/785) ranged from 7 sec for the MYL2.5 model to 0.1 sec for the Garwood model. It must be noted that the models were not necessarily optimized for maximum speed. However, differential (diffusion) models generally require more computation than bulk models because of the need to use a smaller timestep to maintain the accuracy and stability of the vertical diffusion terms. This disadvantage would be somewhat offset on a vectorizing computer because of the high degree of vectorizability of the differential models.

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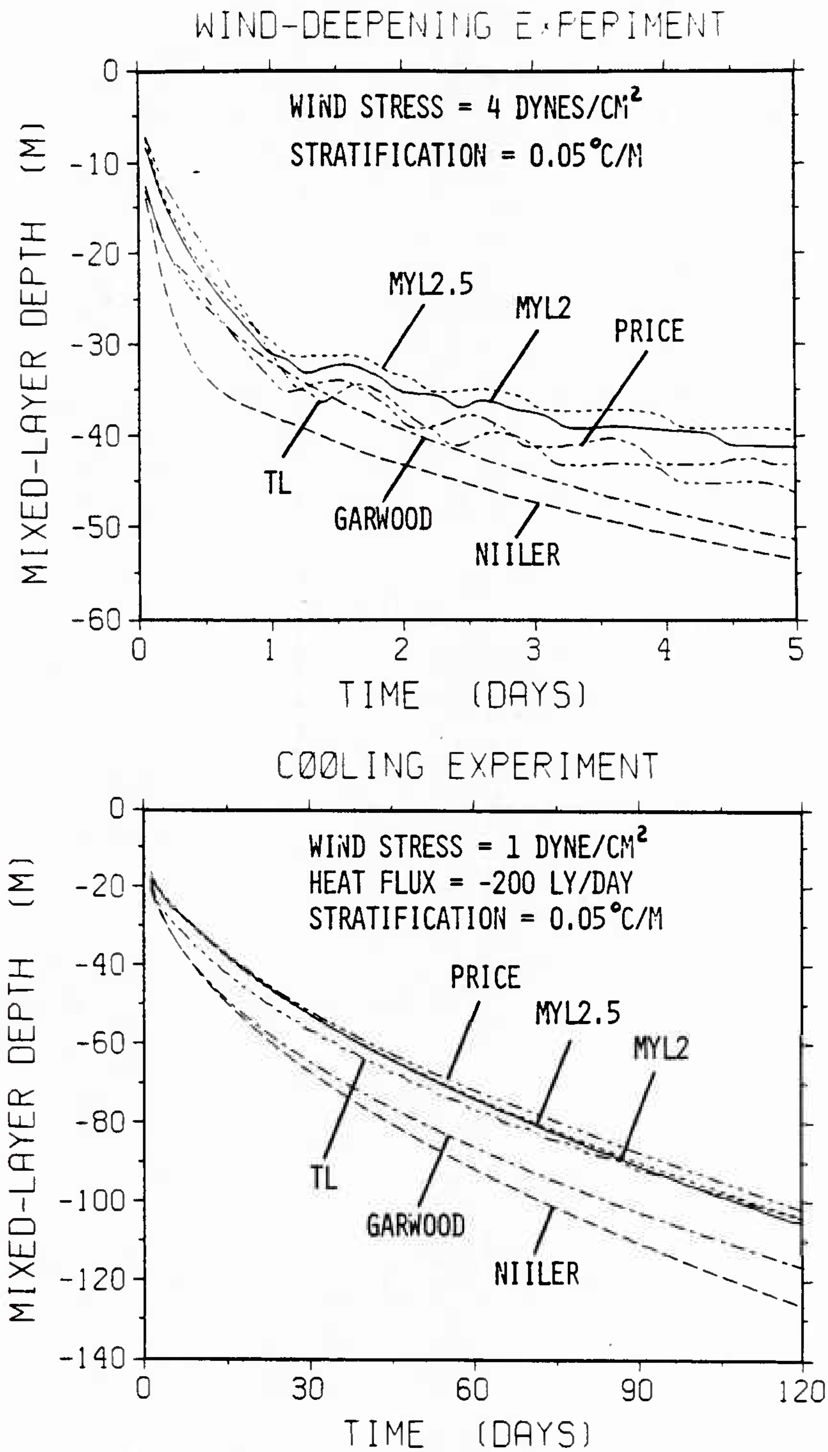


Figure 1. Mixed-layer depth versus time for (a) wind-deepening experiment, and (b) cooling experiment with MYL2 (solid line), MYL2.5 (dotted line), Niiler (dashed line), Garwood (dash-dot line), Price (dash-dot-dot line), and TL (dash-dot-dot-dot line) models.

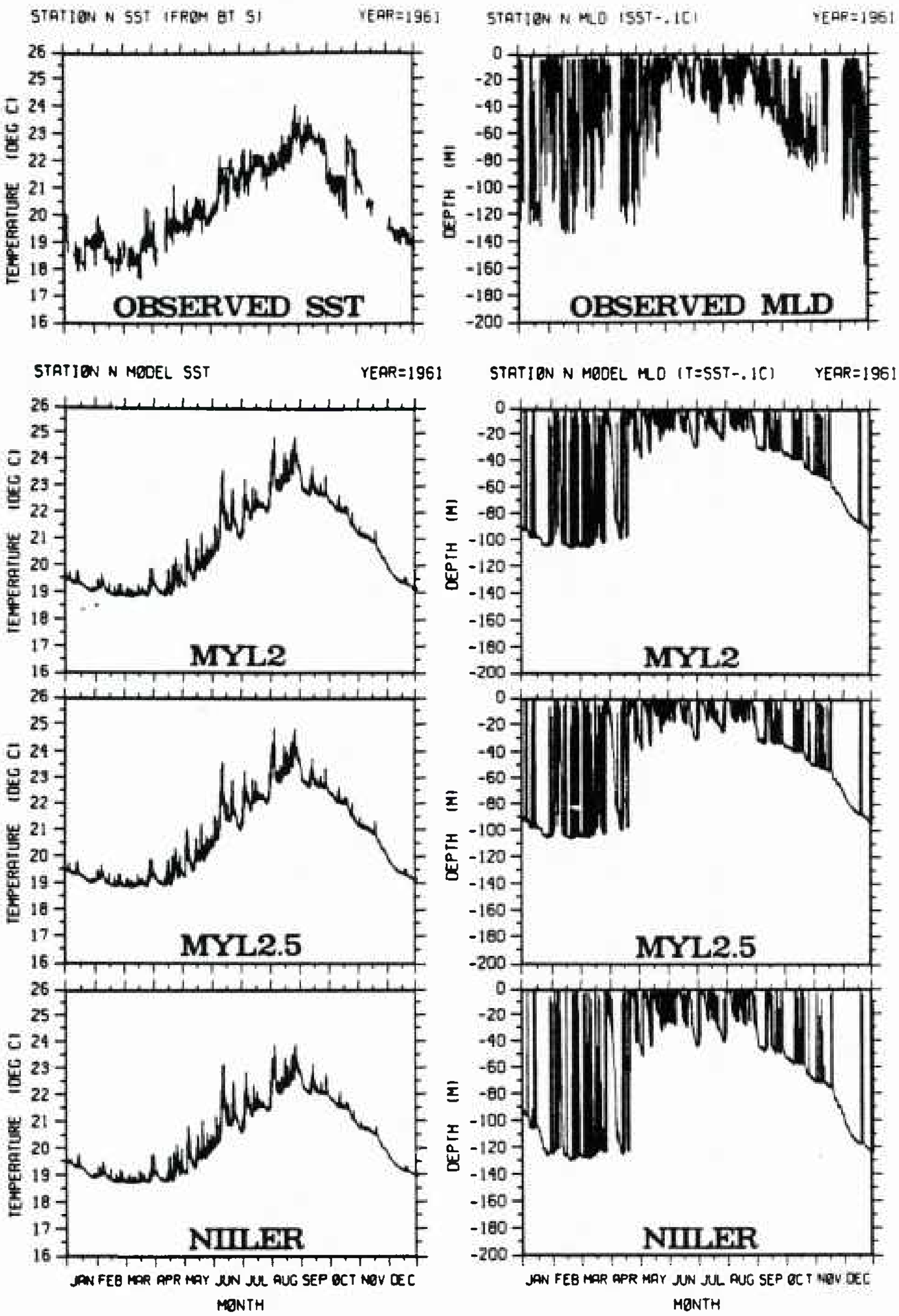


Figure 2a. Observed and predicted SST and MLD at Ocean Station November for the year 1961. Predicted results are for the MYL2, MYL2.5, and Niiler models.

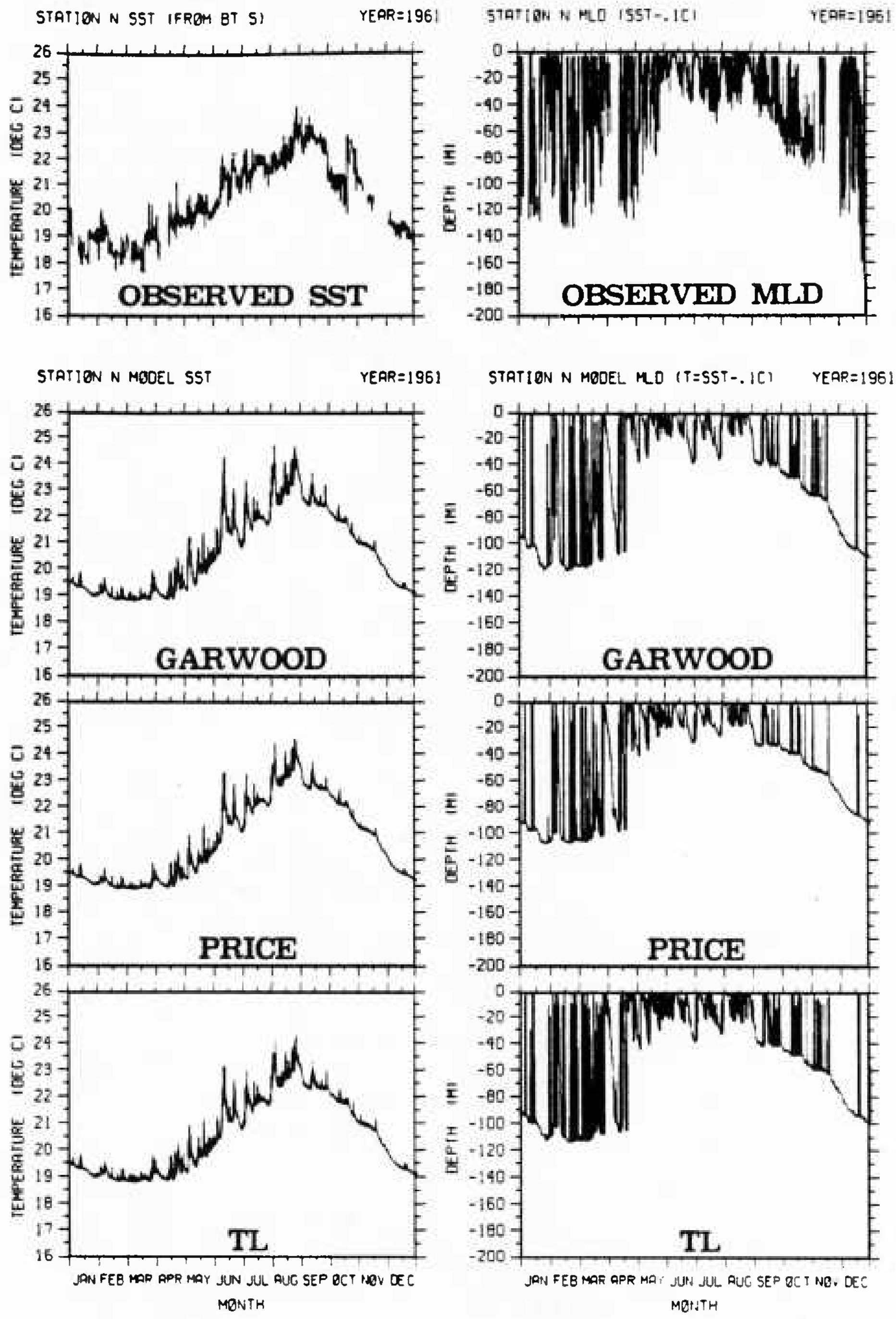


Figure 2b. SST and MLD for Ocean Station November simulations with the Garwood, Price, and TL models.

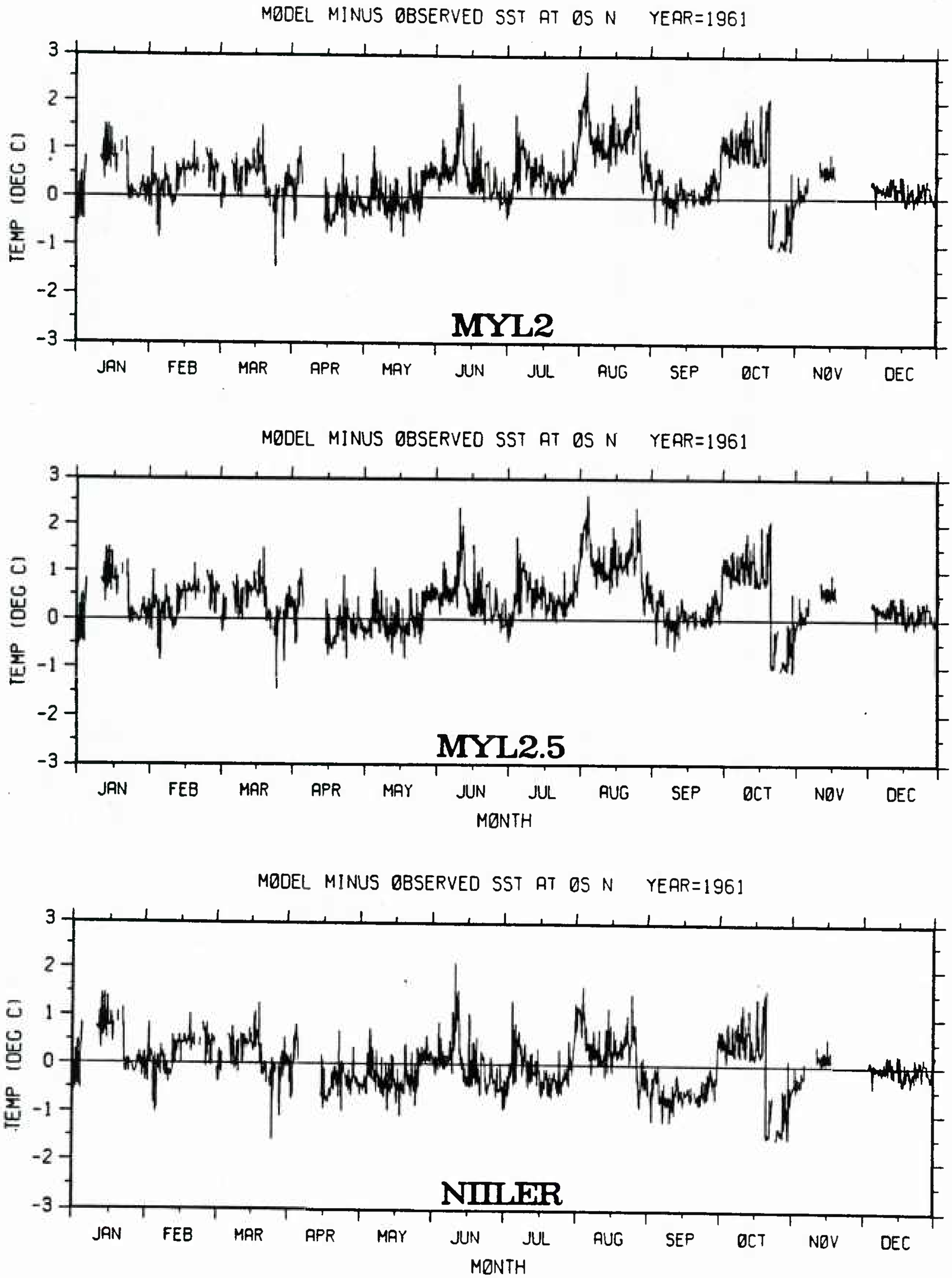


Figure 3a. Difference between predicted and observed SST at November with the MYL2, MYL2.5, and Niiler models.

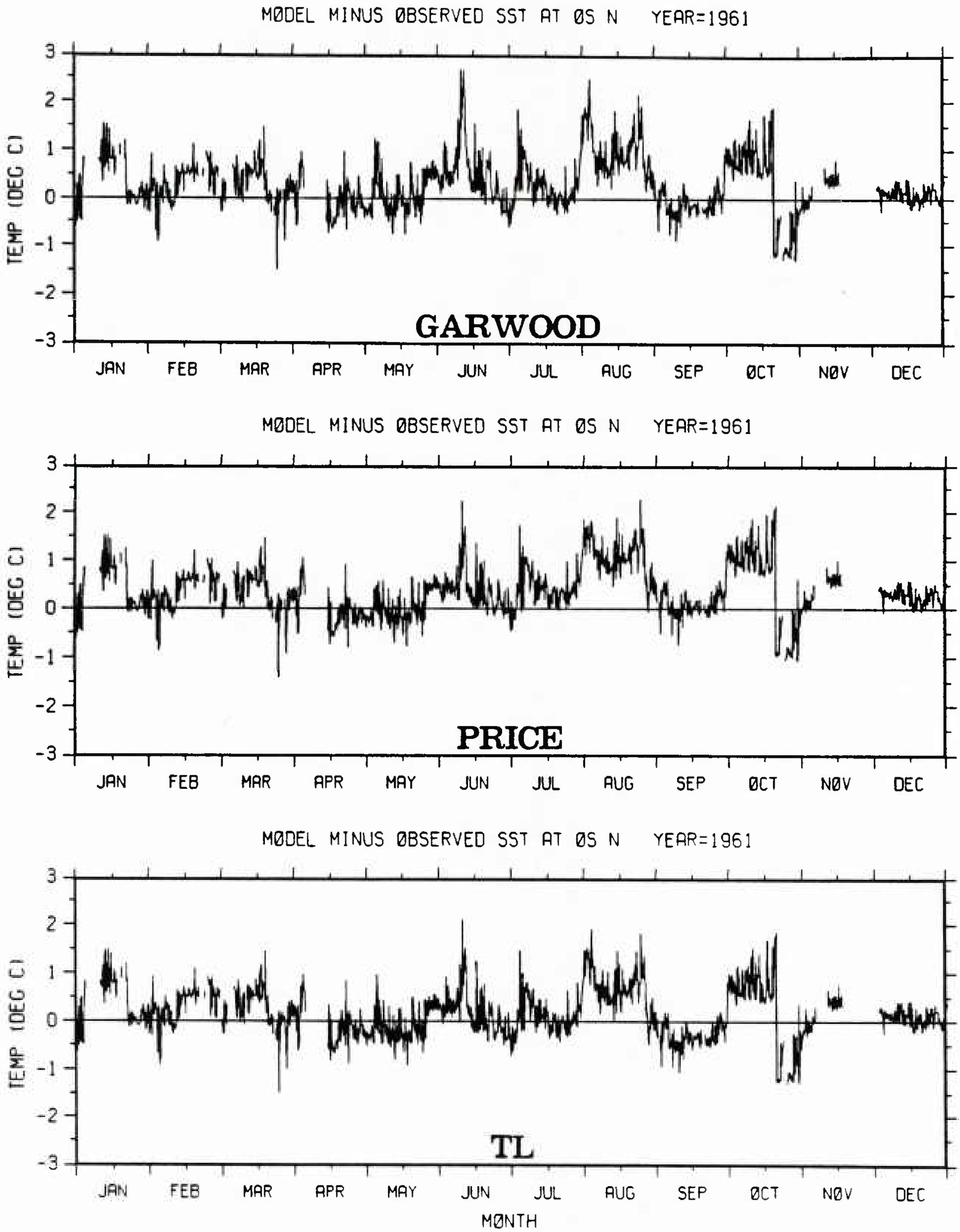


Figure 3b. Difference between predicted and observed SST at November with the Garwood, Price, and TL models.

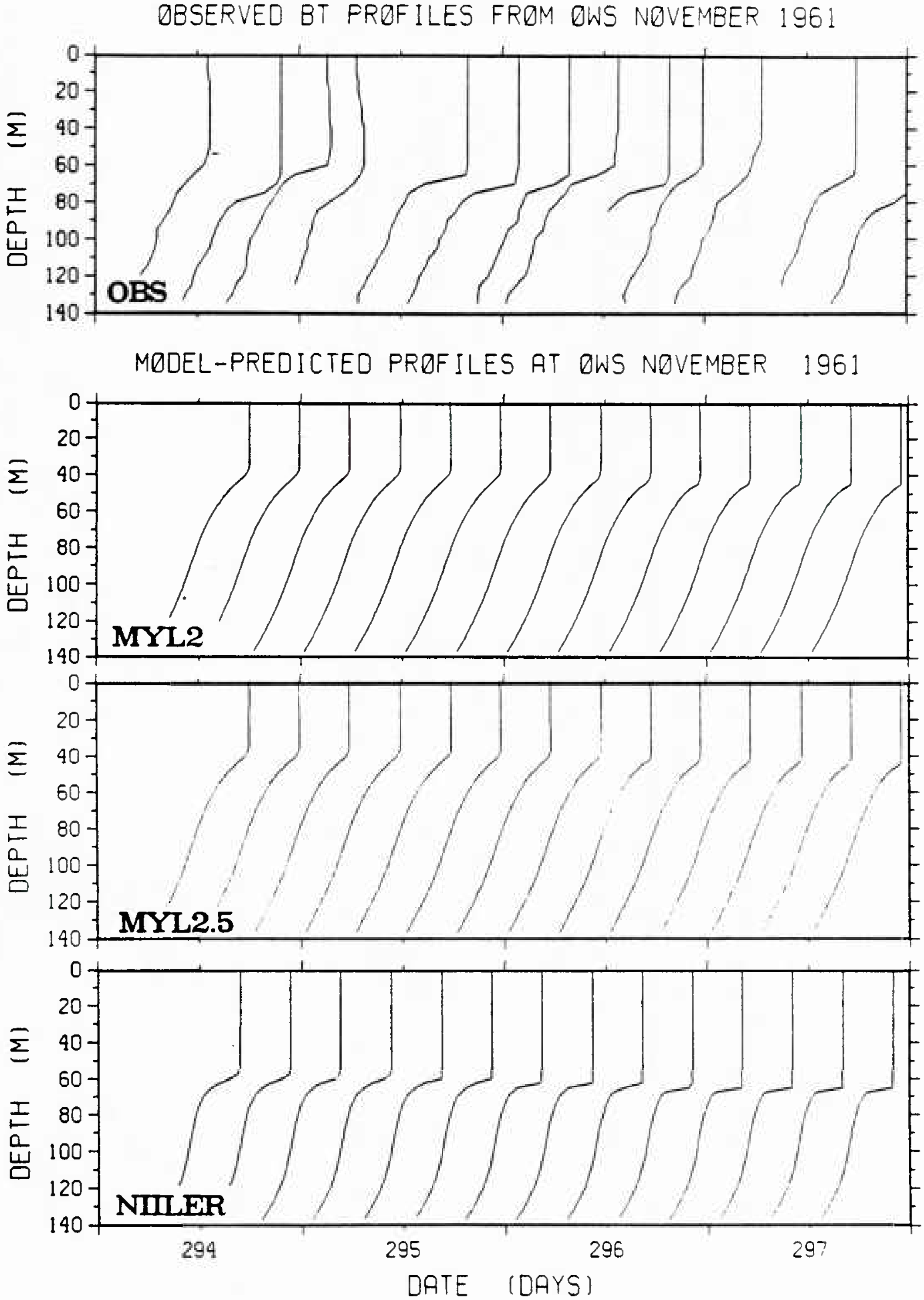


Figure 4a. Observed and predicted profiles at November for a 4-day period near the end of October (October 21–24). Predicted profiles are for the MYL2, MYL2.5, and Niiler models. The horizontal scale is 1 day = 10°C.

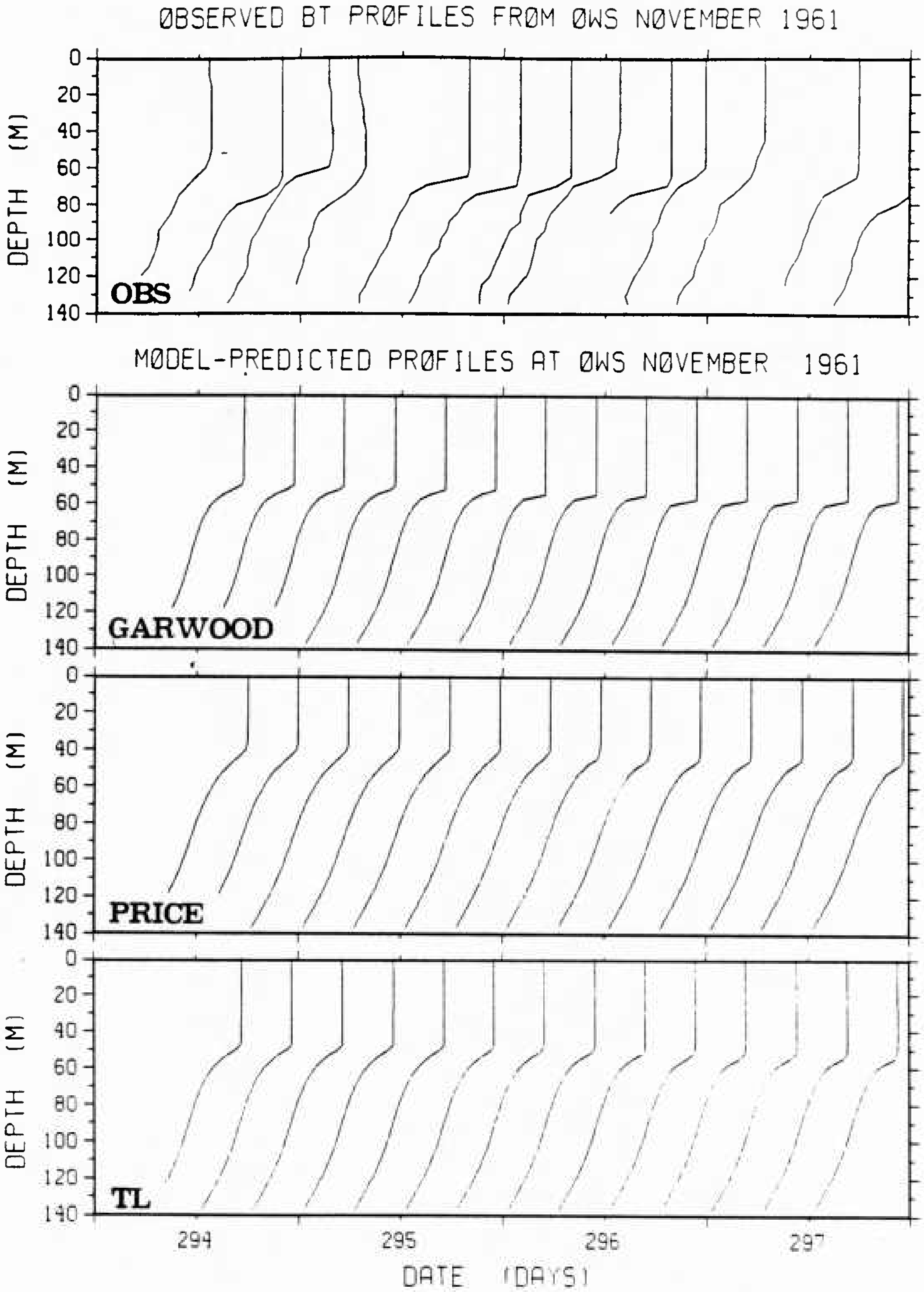


Figure 4b. Observed and predicted profiles at November for a 4-day period near the end of October (October 21–24). Predicted profiles are for the Garwood, Price, and TL models. The horizontal scale is 1 day = 10°C.

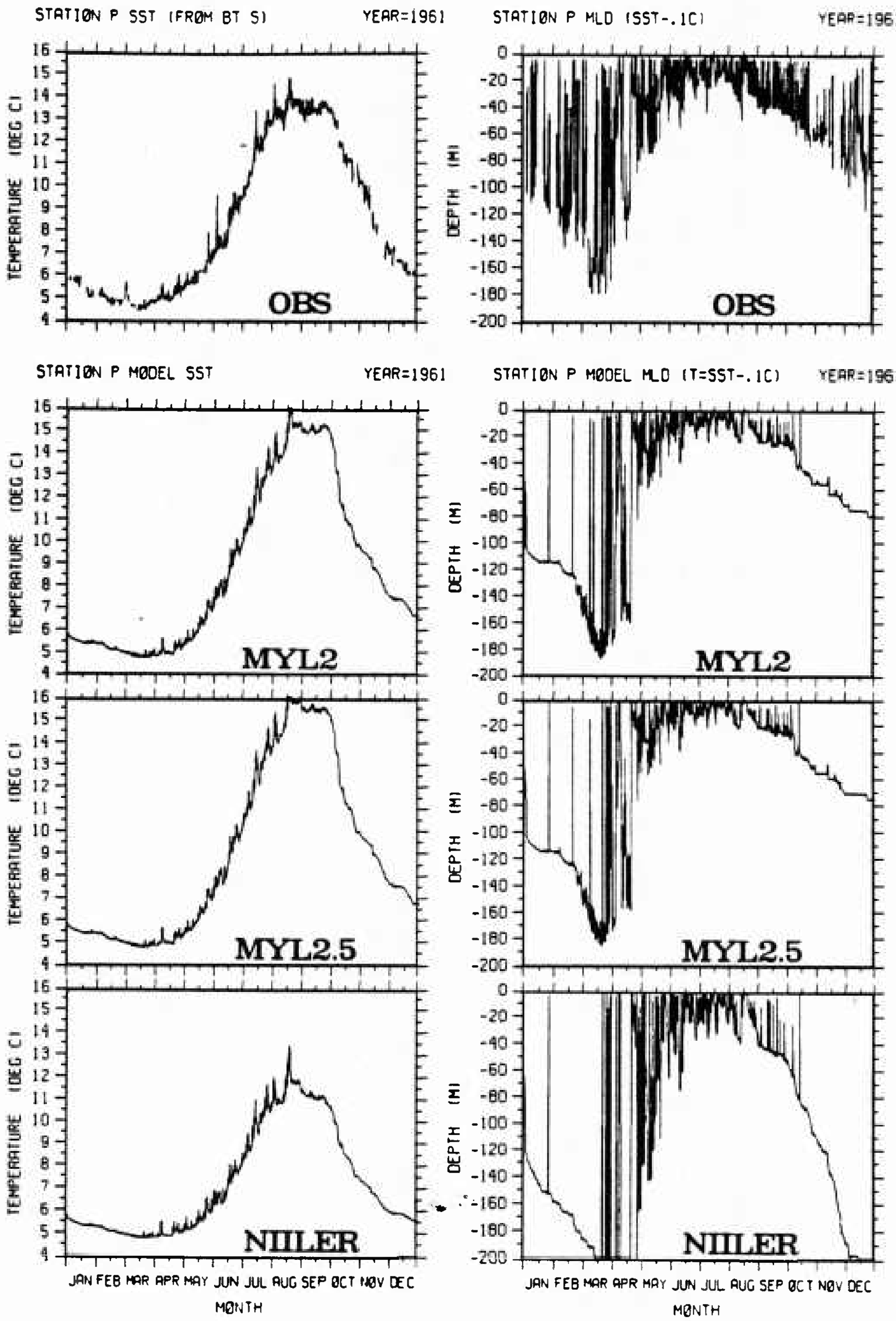


Figure 5a. Observed and predicted SST and MLD at Ocean Station Papa for the year 1961. Predicted results are for the MYL2, MYL2.5, and Niiler models.

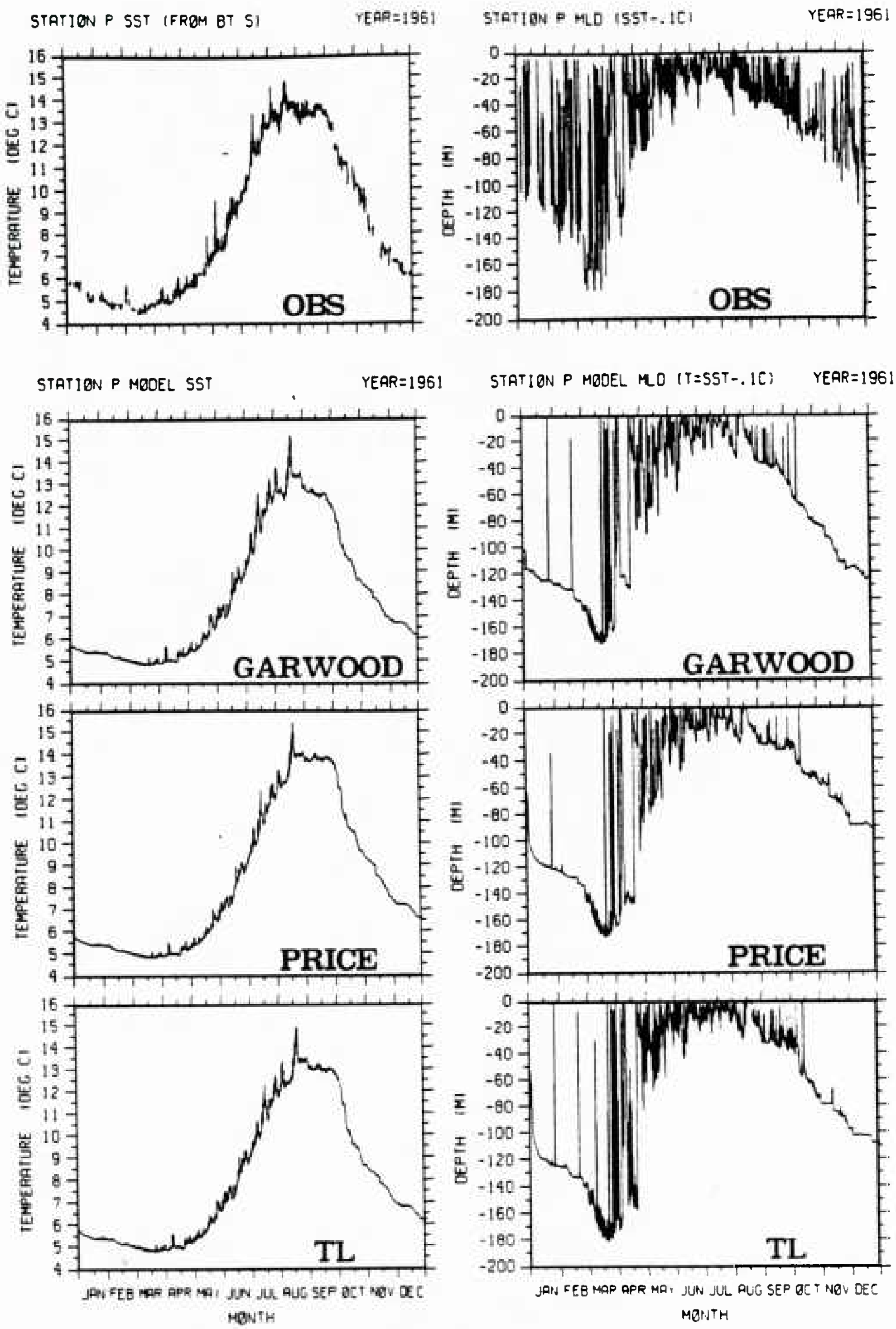


Figure 5b. SST and MLD for Ocean Station Papa simulations with the Garwood, Price, and TL models.

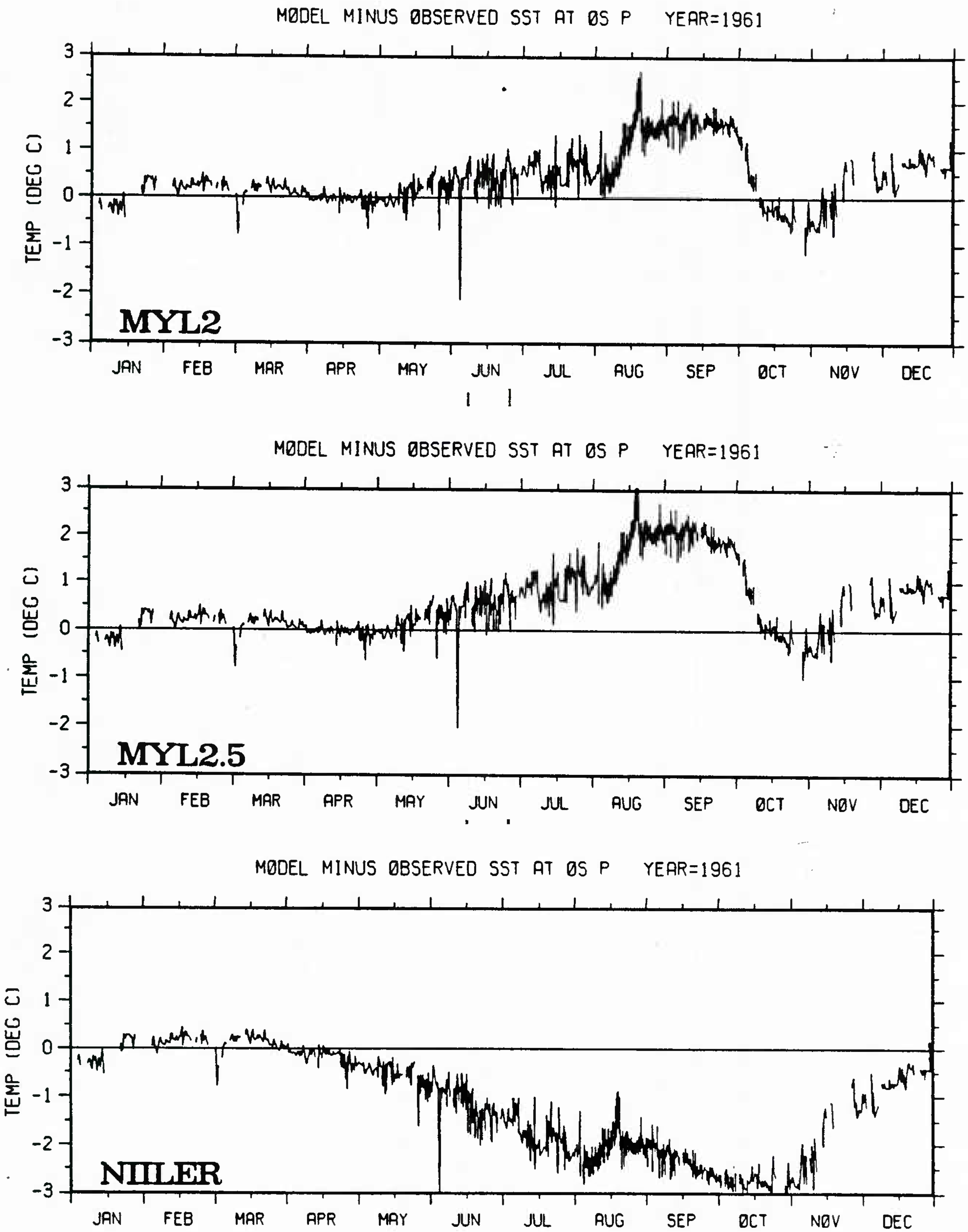


Figure 6a. Difference between predicted and observed SST at Papa with the MYL2, MYL2.5, and Niiler models.

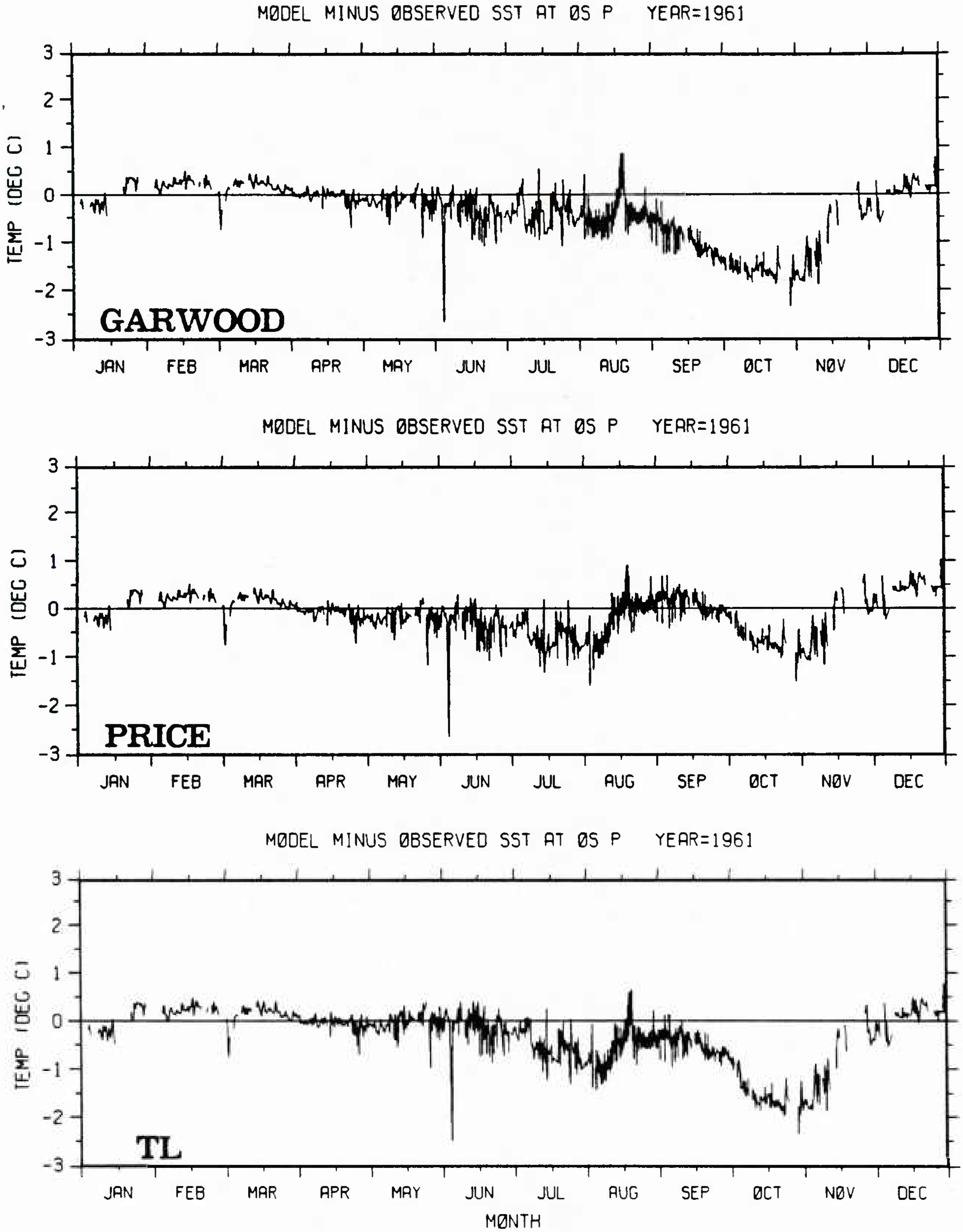


Figure 6b. Difference between predicted and observed SST at Papa with the Garwood, Price, and TL models.

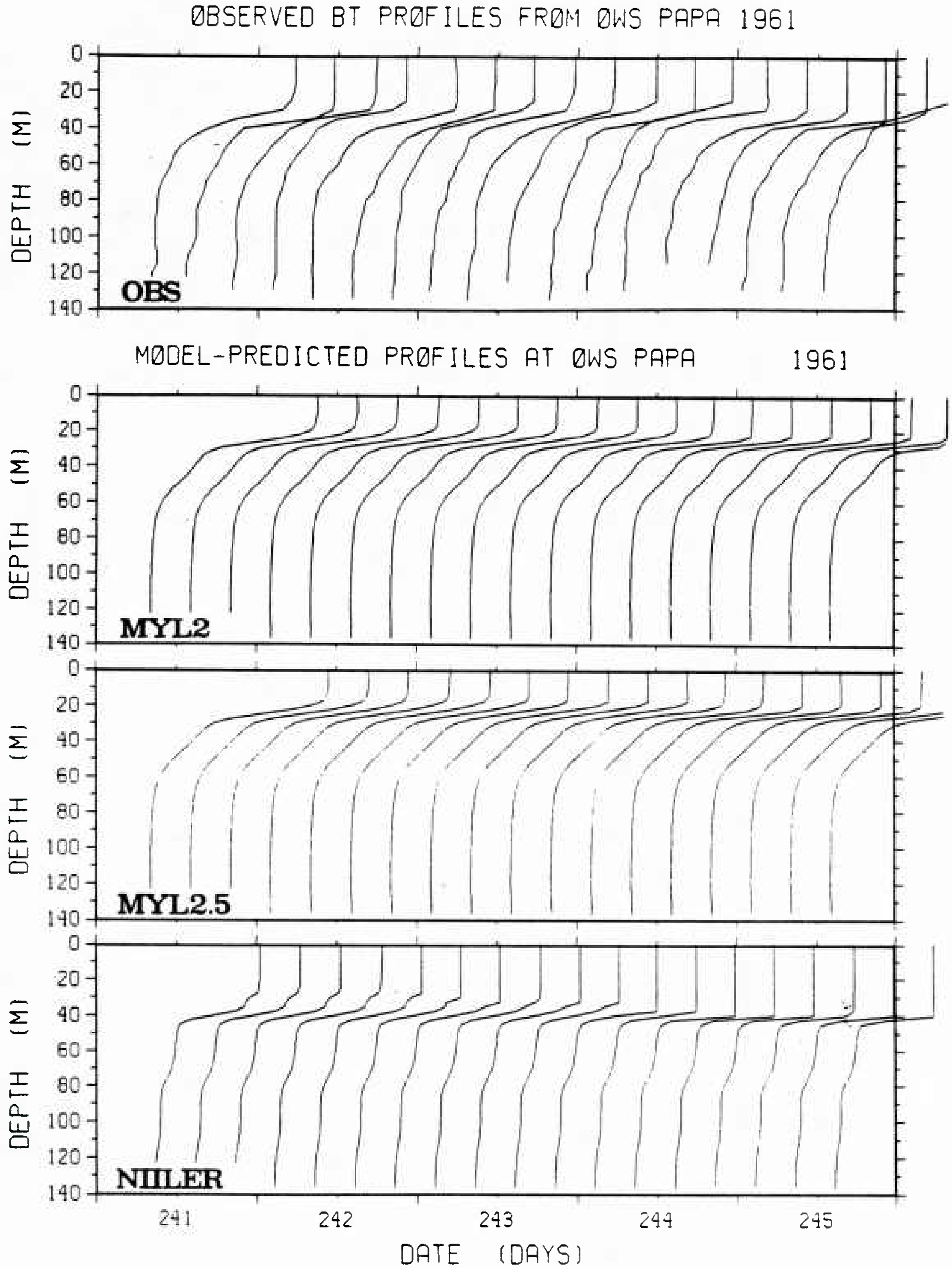


Figure 7a. Observed and predicted profiles at Papa for a 5-day period from August 29 to September 2. Predicted profiles are for the MYL2, MYL2.5, and Niiler models. The horizontal scale is 1 day = 10°C.

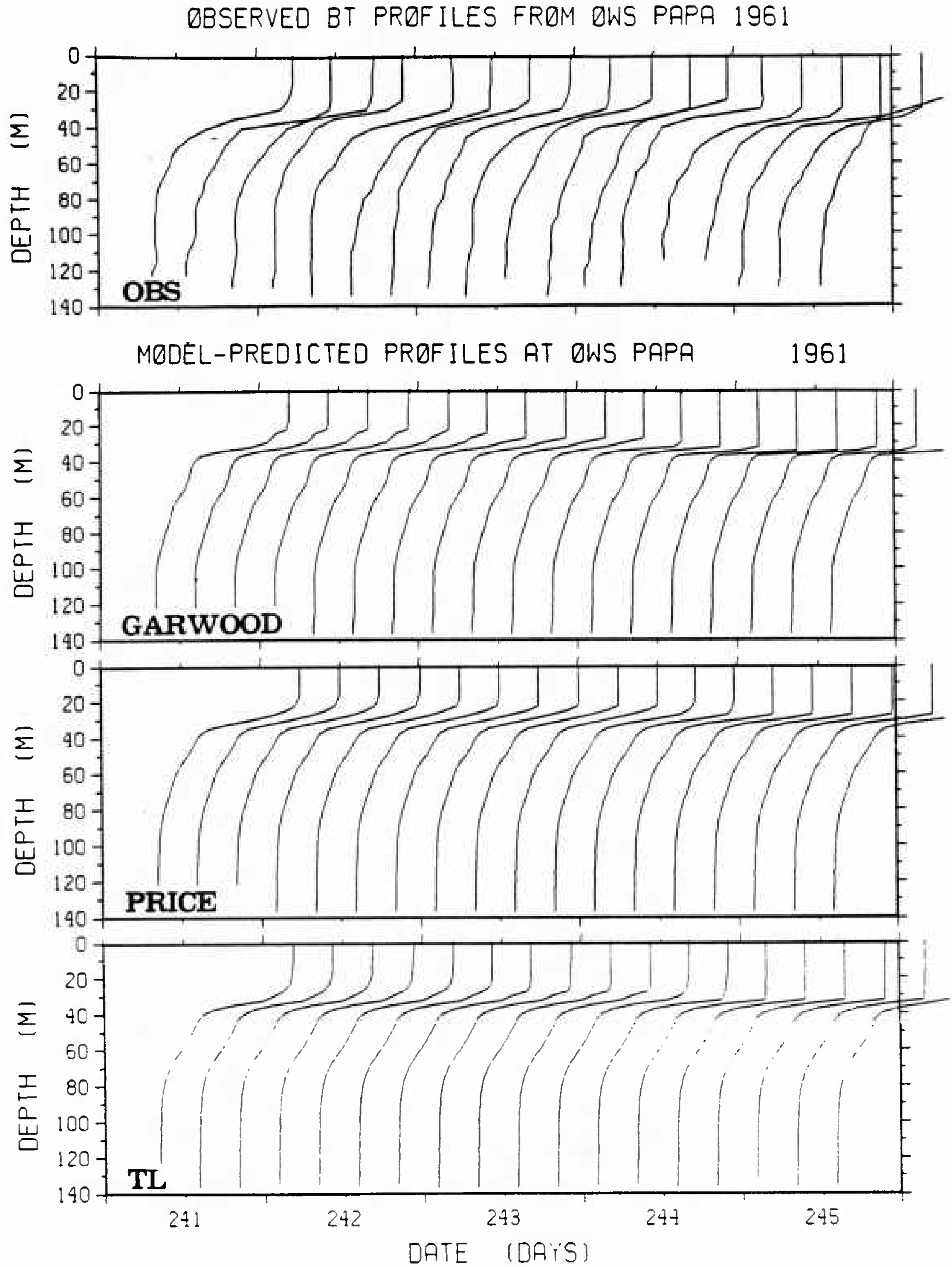


Figure 7b. Observed and predicted profiles at Papa for a 5-day period from August 29 to September 2. Predicted profiles are for the Garwood, Price, and TL models. The horizontal scale is 1 day = 10°C.

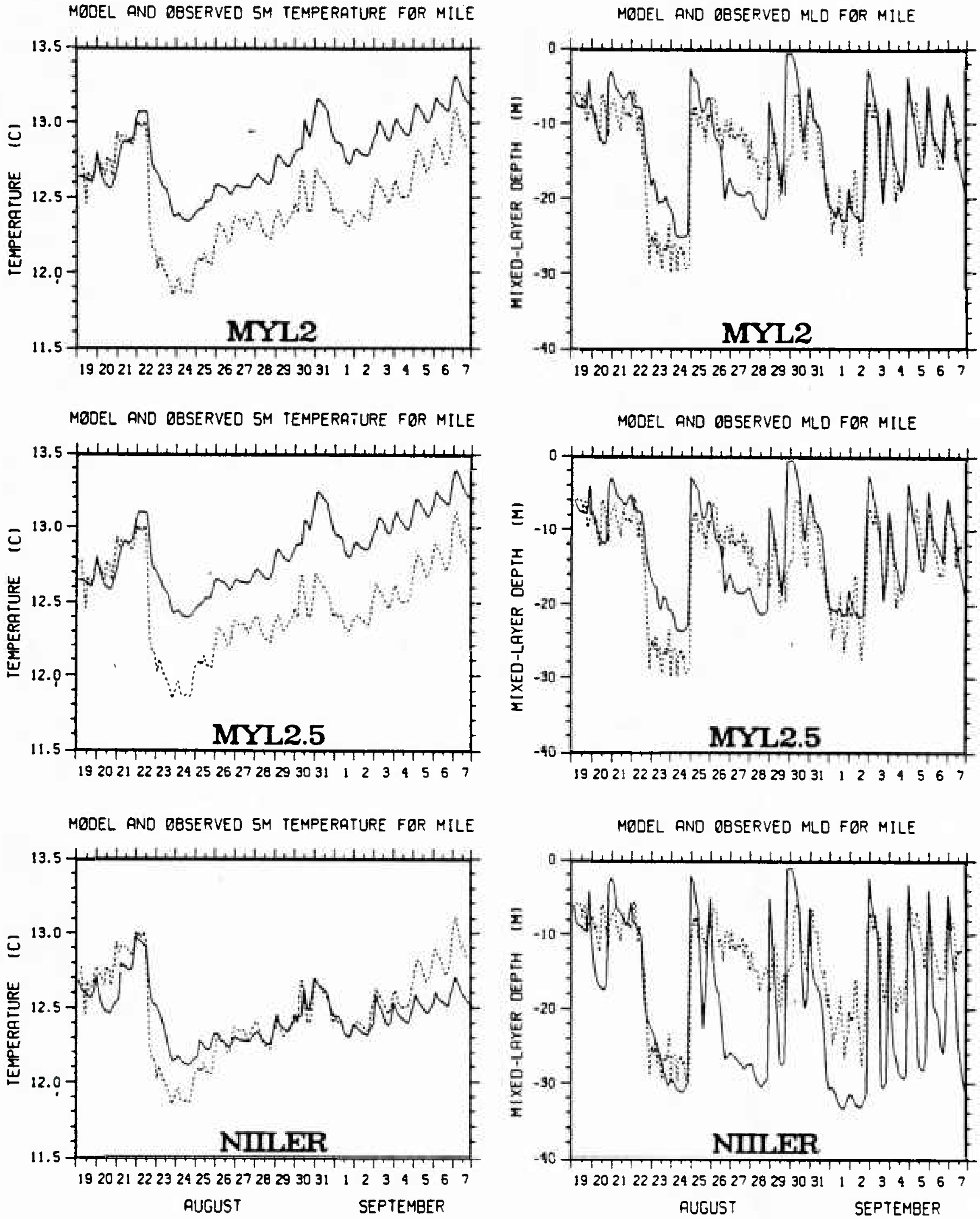


Figure 8a. SST and MLD for simulation of MILE data with MYL2, MYL2.5, and Niiler models. The solid line shows the model results; the dashed line shows the observations.

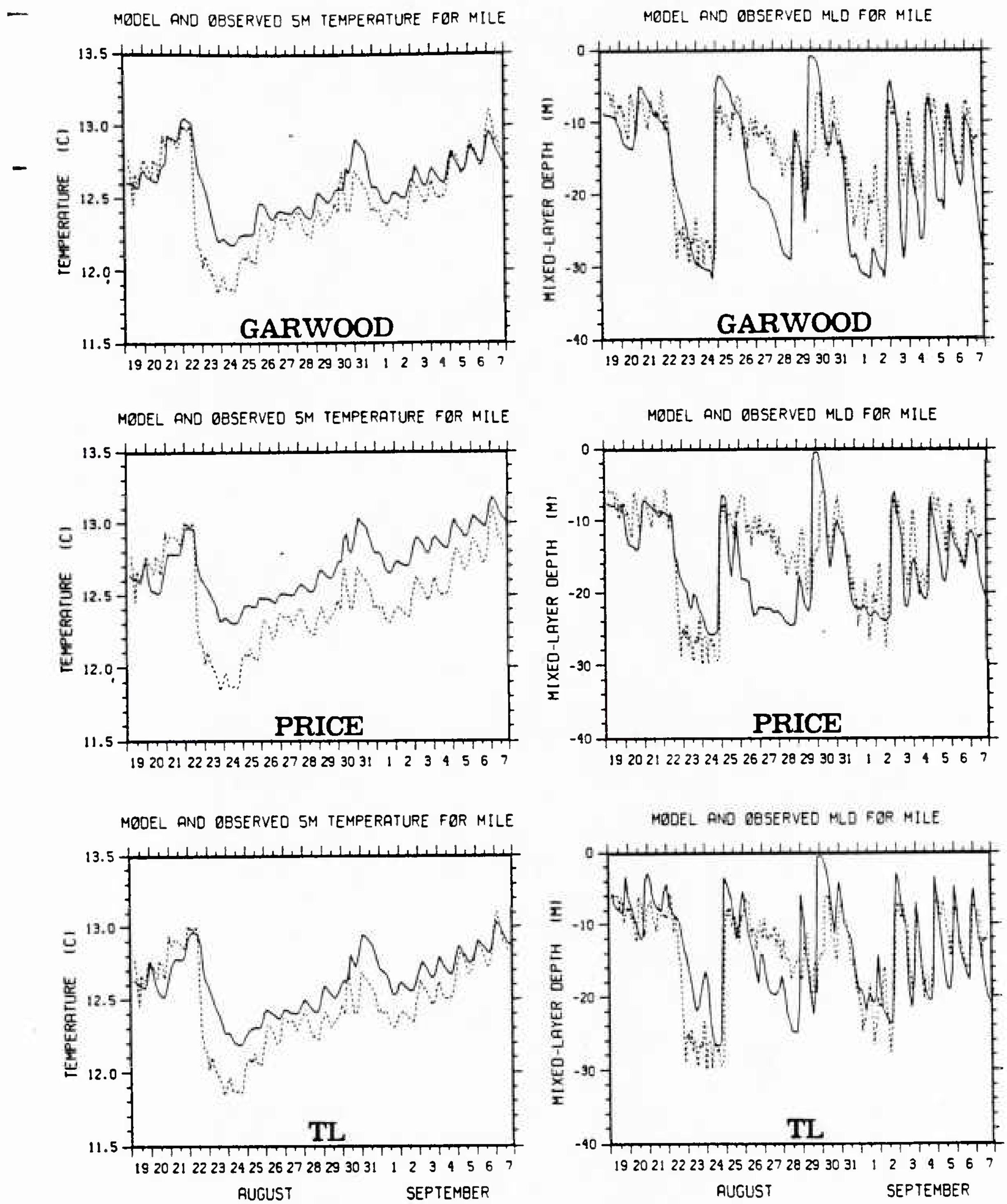
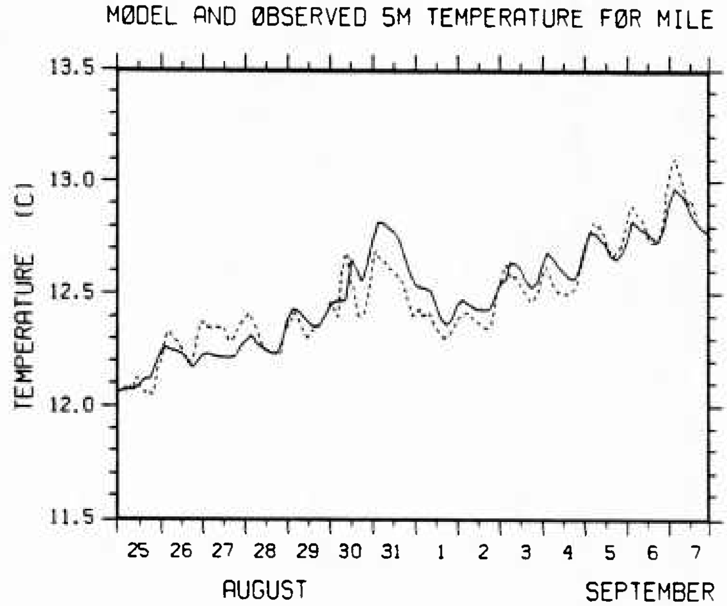


Figure 8b. SST and MLD for simulation of MILE data with Garwood, Price, and TL models. The solid line shows the model results; the dashed line shows the observations.



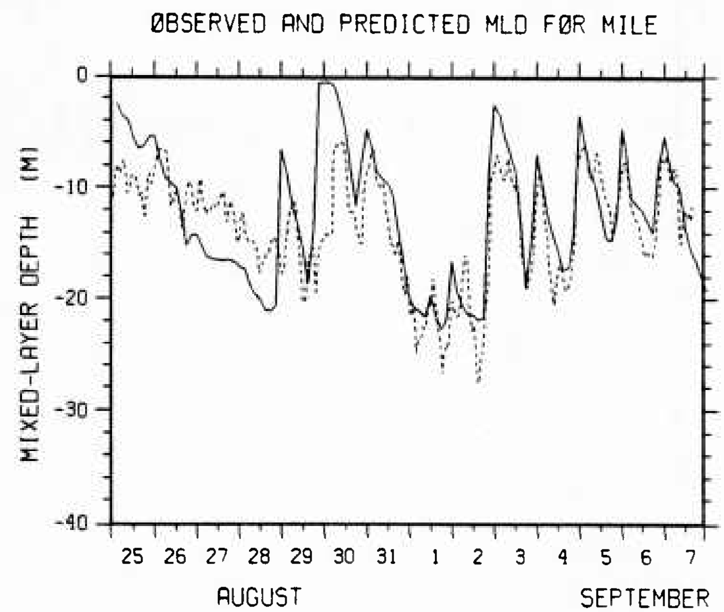


Figure 9. SST and MLD for simulation of MILE data with MYL2 model initialized at 00Z August 25, after the August 22-23 storm. The solid line shows the model results; the dashed line shows the observations.

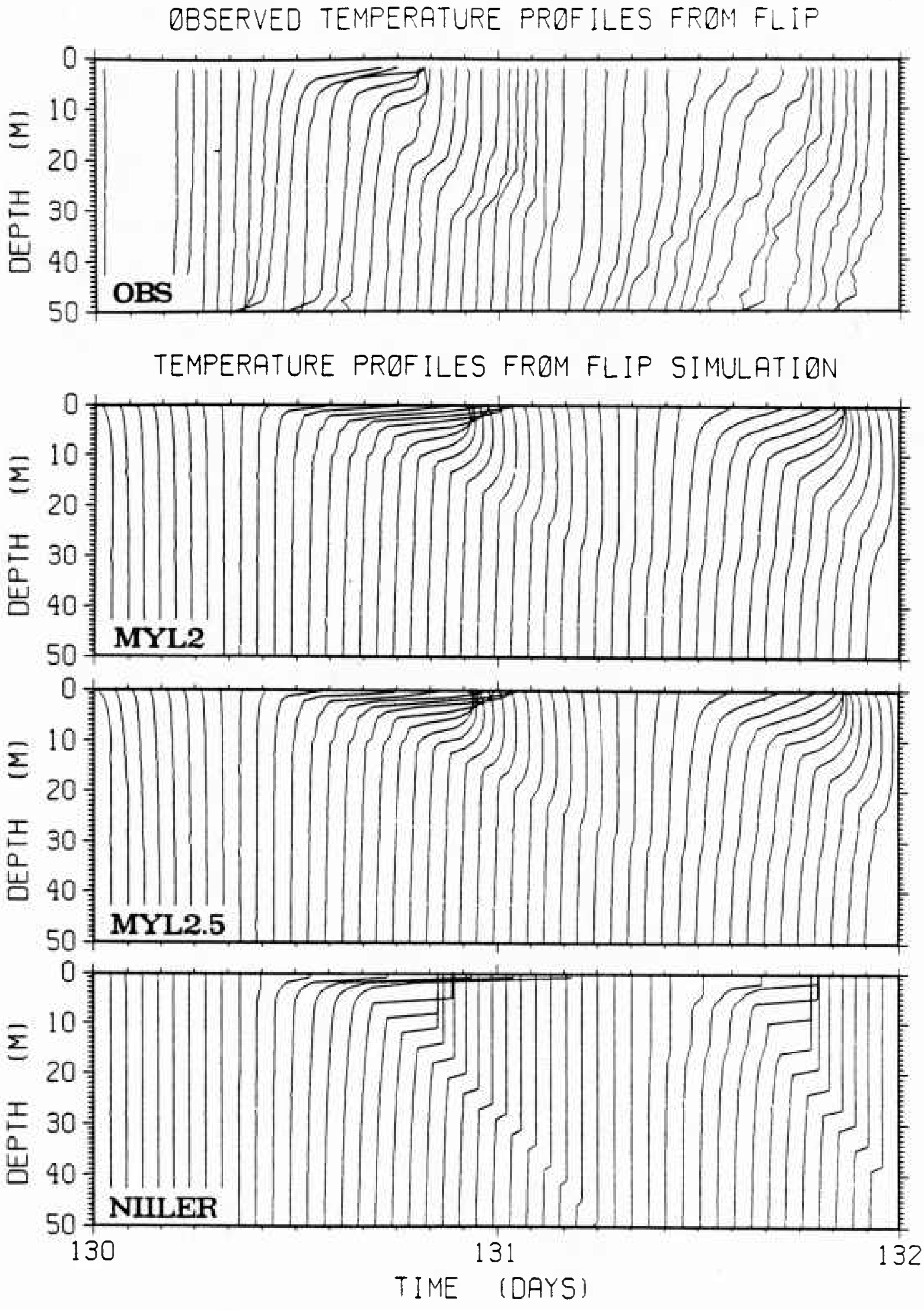


Figure 10a. Observed and predicted temperature profiles for simulation of the data from R/P FLIP for May 9–10, 1980. Predicted profiles are for the MYL2, MYL2.5, and Niiler models. The horizontal scale is 1 day = 1.43°C.

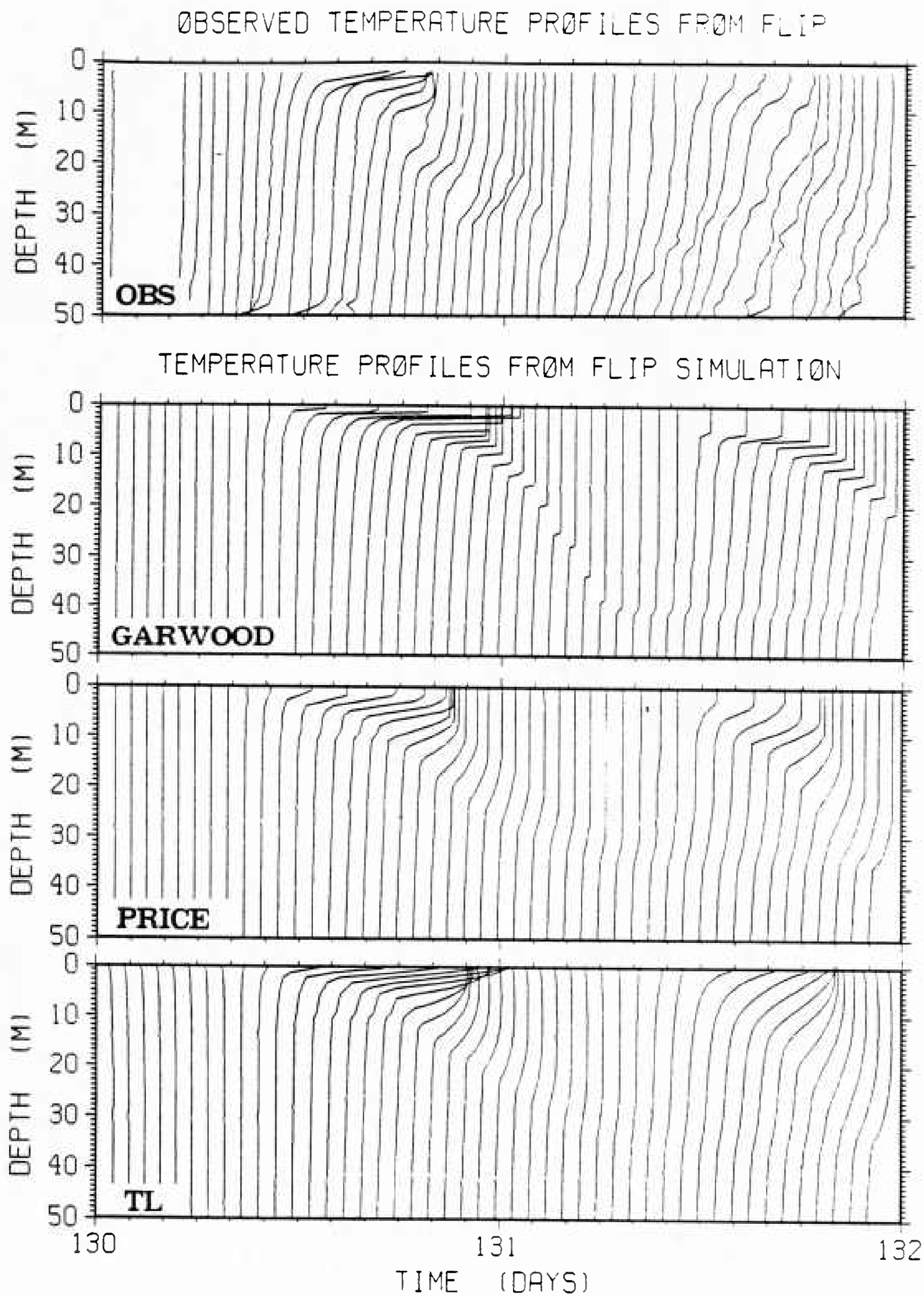


Figure 10b. Observed and predicted temperature profiles for simulation of the data from R/P FLIP for May 9–10, 1980. Predicted profiles are for the Garwood, Price, and TL models. The horizontal scale is 1 day = 1.43 °C.

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Several models of the upper mixed layer of the ocean (Mellor-Yamada Level 2 and 2½, Niiler, Garwood, Price, and Therry-Lacarrere) were compared using (a) idealized forcing that consisted of cases of wind deepening, heating, and cooling, (b) data from Ocean Stations November and Papa, (c) data taken during the Mixed-Layer Experiment (MILE), and (d) data taken from R/P FLIP in the spring of 1980 about 400 km off California. Comparisons with both idealized and observed forcing show the differences among the models to be significant. Differences are especially noticeable for the deepening of the mixed layer in the fall and winter due to wind mixing and convection, and for the shallowing of the mixed layer during light winds and strong heating. Although evaluation of the models is complicated by uncertainties (primarily with regard to advective effects and forcing), the results suggest certain deficiencies in some of the mixing parameterizations. Keywords: Mixed layer (Marine); Ocean models; Pacific Ocean; Air water interactions.

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